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WATER RESOURCE APPLICATIONS, UNDERGROUND STORAGE OF NATURAL GAS, AND WASTE DISPOSAL USING UNDERGROUND NUCLEAR EXPLOSIONS

by

Gerald D. Cohen and Francis M. Sand

Prepared for
U. S. Atomic Energy Commission
Washington, D. C.

MATHEMATICA
One Palmer Square
Princeton, New Jersey

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Nuclear Explosions—Peaceful Applications
(TID-4500)

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August 31, 1967

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FOREWARD

Since the Plowshare Program was established in 1957 to investigate and develop peaceful uses for nuclear explosives, a large number and variety of applications have been suggested. As a result of the Plowshare research effort, many suggestions have been discarded for technical reasons while others have been more clearly identified as long-range possibilities requiring still more data and further development. Other ideas have now been sufficiently developed and offer enough promise to warrant the type of pilot-scale or prototype experiment needed to obtain precise information in an industrial framework.

By the time such an experiment is seriously considered and proposed, there is a need for some general economic appraisal of the potential value of the application. In the course of research some economic information is usually generated; however, for the most part, the AEC has relied primarily on government agencies responsible for resource development and on industry for information and general economic evaluations. As a result, this information and analysis is scattered throughout different reports, and appraisals have often been made on different bases and with different assumptions and resource information. Since a number of these applications are now approaching a commercial technology level, it seems timely and desirable to make some effort to collect this information, put it on as consistent a basis as possible, place it in the proper economic and resource perspective, and include enough relevant technical and cost information about nuclear explosions, their effects and associated operations, to permit a better and more detailed analysis from an economic point of view.

To these ends, Mathematica Incorporated of Princeton, New Jersey, was engaged to carry out this assignment. They have produced a series of reports covering the various areas of application for peaceful nuclear explosions and a general summary report. These reports are not intended to be definitive economic analyses, since sufficient data is still not available for such analysis. Rather, these studies are intended to serve as a beginning point and a means of identifying on a consistent basis the range of potential of the presently known, most promising applications. It is hoped that they will serve as a useful guide for future economic studies, especially by identifying key technical questions which affect the economics of the applications, such as whether the fractured area of oil shale surrounding the nuclear chimney can also be retorted. It is towards answering these key technical questions that much research and development, including the design of current experiments, is being devoted. Beyond the identification of key technical questions, these studies attempt to define the controlling economic parameters for the different applications, such as the diameter of explosives and concomitantly the cost of very deep drill holes for the gas production stimulation applications.

With the expectation that this information will be of general interest, as well as a guide for the research of those working in Plowshare, the AEC is pleased to make these reports available.

John S. Kelly, Director
Division of Peaceful
Nuclear Explosives

ABSTRACT

This report is a collection of three separate papers dealing with "Water Resource Applications of Plowshare in the United States," "Underground Storage of Natural Gas in Nuclear Cavities," and "Waste Disposal." The first of the papers was written by Gerald D. Cohen; the latter two by Francis M. Sand. During the writing of these reports a variety of difficulties were encountered in the economic evaluation of each of these peaceful applications of nuclear explosives, among them difficulties in projecting potential demand for these processes, uncertainties regarding technical questions due to the lack of nuclear experiments in all three cases, and as a consequence quite some uncertainty must also be attached to the economic benefits and costs of these processes. The main results of the three reports are:

In the case of Water Resource Applications within the United States, we concluded that on a national scale the United States is endowed with ample water resources. Only in selected regional situations water shortages appear imminent as the population increases. Extending present trends in water consumption and management, by the end of this century 22 river basins in the United States may not have local supplies of water sufficient to support further development. Four different approaches to

solve this problem were proposed, and in each of them, nuclear explosives could be used at some stage:

1. Increase the storage capacity of water on or beneath the land surface. Such storage space could be created either by throwout and subsidence craters or by nuclear chimneys deep underground. The cost of crater reservoirs appears to be within feasible range. The main advantage of using nuclear chimneys for water storage is that they are not subject to the heavy evaporation losses of surface reservoirs. Nuclear chimneys may also be used in water recharge projects--a potentially major Plowshare application if technical uncertainties are eliminated by nuclear experiments.

2. Apply nuclear explosions in water treatment projects, in the form of alternate waste disposal sites. Other means were found to be less expensive in most cases. However, under critical circumstances it offers a solution if the only other solution is to stop production.

3. Make available new supplies of water by tapping very deep aquifers. Management and recharge of aquifers would be subject to more effective control and this may be a significant factor in semi-drought areas. Other applications in this field include the breaching of separate aquifer systems, and tapping of perched water bodies; but various political difficulties will arise in such projects which may outweigh the technical and engineering uncertainties.

4. Reduce evaporation losses by underground storage in nuclear chimneys. Though this is a desirable side effect of water storage by

nuclear explosives, it is not a determining factor if alternate storage capabilities are available.

In all water resource management projects, safety, and in particular, radiological safety, will ultimately decide whether Plowshare can be used in this field. A phased series of test shots designed especially for these uses would be immensely important in clarifying the possibilities and timing of applications in water resource management.

The Underground Storage of Natural Gas seems, overall, to be one of the Plowshare applications with the least technical engineering uncertainties: product contamination may be overcome in this case more easily, as the consumer good is not present around the shot point at the time of detonation and decontamination of the storage site would be possible before any natural gas is stored in the nuclear chimney. The other cost figures of the nuclear process compare favorably with conventional costs. Thus the nuclear method of creating new underground gas reservoirs appears to have great promise in a number of specific areas. As in all other fields, however, there is again an indication that experimental programs should be undertaken before a major commitment of public or private funds is considered for widespread applications. The investment costs per thousand cubic feet (=MCF) of storage for a 20-50 KT nuclear reservoir at 2-4000 feet below ground level are in the range of \$1 to \$4. These costs compare favorably with some methods of creating gas storage such as liquid natural gas storage (\$4 to \$6.45), storage in steel pipes

($110 to $207) and unfavorably with other underground methods (average $ .17). In terms of deliverability, the comparison is most favorable to the nuclear method ($1.43 to $2.09 as against an average of $46.50 for conventional storage fields). Further research on the geologic settings and of locations for feasible application is indicated. Of particular importance in any such experiments is again the exact determination of the extent and costs of safety considerations.

The last peaceful application of nuclear explosives discussed in this report concerns Waste Disposal. The disposal of sewage and industrial effluents has received a vastly increased amount of attention in recent years. Although many alternative methods exist dealing effectively with waste disposal problems, the report concludes that the application of nuclear explosives for creating underground storage for harmful wastes is an alternative to the existing methods which at present do not appear to demand substantive investment of resources, but which could prove to be a valuable addition to the Federal anti-pollution program particularly if used in conjunction with a regional resource management scheme.

Chapter 1

WATER RESOURCE APPLICATIONS OF PLOWSHARE IN THE UNITED STATES

1.1 INTRODUCTION

Water use in the United States is increasing as swiftly as the population. By the end of the century the total water withdrawal rate will reach 75 per cent of the present usable rain runoff. This indicates that a very considerable increase in the capture of runoff and its conservation and storage will be necessary. Total capital costs for providing the increased facilities will exceed 100 billion dollars. Opportunities for widespread use of new techniques exist in this situation. One of these techniques may be the use of nuclear explosives to excavate reservoirs and water conveyance channels on the surface of the land as well as alter the permeability to groundwater flow beneath the surface. Projects with a large degree of excavation seem to offer short term feasibility, and will undoubtedly receive attention in the wake of the studies being conducted for a new Isthmian Canal. Many other suggested nuclear (Plowshare) applications in the water resource field do not propose to have current economic or practical feasibility in the United States. However, in special critical water short situations the value of water rises so steeply that the economic factor, in particular, can be outweighed by necessity.

This report is a summary of the types of applications proposed for Plowshare in the water resource field. First the magnitude of the water supply problem in the United States is outlined, then the structures created by a nuclear explosion are described, and lastly the application of these structures to specific problems is discussed.

1.2 WATER REQUIREMENTS AND SUPPLY IN THE UNITED STATES

The 3,000,000 square miles of the continental United States are covered each year with an average of 30 inches of rain. The yield in runoff to the nation's rivers and streams is 1,200 billion gallons per day (bgd). This self-replenishing resource is used and recycled many times in its travel to the two oceans and the Gulf of Mexico. Upstream municipalities, industrial and thermal electric plants withdraw vast quantities and return most of it for re-use by others further downstream. Water which is not returned via this route is considered 'depleted.'

The projections of future water withdrawals and depletions indicate a very large increase by the end of the century. Water use will keep up with and may surpass the rate of population increase. The doubling of the 1954 population by the year 2000 (from 165 million to 331 million people) is expected to double the depletion rate (from 70.5 to 149.1 bgd) and almost triple the withdrawal rate (from 300 to 888 bgd).

Table 1.1--Fresh Water Withdrawals (bgd)

	1954	1980	2000
Municipal Use	17	29	42
Thermal Electric Power	74	259	429
Manufacturing and Mining	33	105	233
Irrigation and Agriculture	176	167	184
U. S. Total	300	559	888

SOURCE: U. S. Senate Select Committee on National Water Resources, August 1960, Committee Print No. 32.

Table 1. 2--Fresh Water Depletion (bgd)

	1954	1980	2000
Municipal Use	5. 9	10. 8	15. 9
Thermal Electric Power	. 3	. 8	1. 3
Manufacturing and Mining	3. 0	8. 2	16. 8
Irrigation and Agriculture	61. 3	86. 7	115. 1
U. S. Total	70. 5	106. 5	149. 1

SOURCE: "Resources in America's Future, Patterns of Requirements and Availabilities 1960-2000," Resources for the Future, Johns Hopkins Press, 1963.

The supply of water available in the United States will be adequate in total to meet the demand but because of three factors, there may be severe local shortages. The complicating factors are:

1. Lack of geographical uniformity of rainfall: On a regional basis some areas of the United States may not have rainfall or streamflow sufficient to support estimated population increases. The disparity of rainfall is extreme between the western desert regions where only 1 to 5 inches fall and the Pacific Northwest where 80 inches may fall. Of the 22 river basin regions defined by the U. S. Geological Survey it is possible that five will not have the potential supplies capable of being developed by conventional technology.

2. Imbalance of seasonal rainfall: In most areas of the United States spring rains and thaw of snow release the greatest portion of the annual water supply, often in flood proportions. The potential to divert, capture and store this water in conventionally constructed surface reservoirs is limited by the number and size of suitable reservoir sites and

the runoff pattern. Table 1.4 contains projections of how much additional surface storage capacity will be necessary by the end of the century to meet the water requirements in each of the 22 regions. In the regions marked with an asterisk little or no excess supply is expected to be available after 1980, and with a double asterisk for no excess after 2000.

3. Deterioration of water quantity: The re-cycle ratio for water withdrawn to depleted for all uses except irrigation is about 13.5 to 1. This means that for every 13.5 gallons withdrawn 12.5 gallons are returned to the water environment. However, different kinds of use produce changes in water quality which render it less acceptable for other uses. Organic wastes from municipalities and industry in particular exert a high demand for dissolved oxygen in water. When the oxygen level falls too low, fish die, bacteria thrive, and the visible effects of pollution become apparent. While the water is usually capable of recovering from the demand of the waste load, it requires the addition of fresh dilution water. In the eastern part of the United States, it is estimated [217] that flow requirements for dilution purposes will become the major determinant of water policy by the year 2000. In the New England region it is estimated that by the year 2000, 2.5 bgd of water will be used and lost from runoff while 16.9 bgd will be required for waste dilution purposes (90 per cent).

1.3 COST OF MEETING FUTURE WATER REQUIREMENTS

In order to provide the surface storage reservoirs for future withdrawal and waste dilution uses and new waste treatment facilities, a considerable and sustained annual capital investment is required. There is a "trade-off" between storage and treatment since increased

Table 1.3--Withdrawal vs. Remaining Supply (bgd)

River Basins	1954	1980	2000	Supply Remaining (1954)
New England	6.3	18.0	30.3	67.
Delaware and Hudson	14.7	35.7	58.7	32.**
Chesapeake Bay	7.1	20.8	36.0	52.
Southeast	11.2	39.2	73.2	212.
Eastern Great Lakes	11.2	32.4	58.2	40.**
Western Great Lakes	13.0	37.9	65.4	42.**
Ohio	22.0	67.2	110.7	110.
Cumberland	.2	.5	1.9	17.
Tennessee	3.7	11.8	24.4	43.
Upper Mississippi	8.4	22.5	39.9	62.
Lower Mississippi	4.5	8.7	15.9	49.
Upper Missouri	27.9	33.9	47.2	19.*
Lower Missouri	1.3	2.6	6.4	23.
Upper Arkansas-White-Red	8.4	12.1	16.5	11.
Lower Arkansas-White-Red	3.8	7.1	11.4	77.
Western Gulf	22.7	43.0	78.9	46.
Upper Rio Grande and Pecos	8.9	10.2	10.7	(-)*
Colorado	26.7	27.6	30.0	3.2*
Great Basin	12.6	13.1	13.3	3.7*
Pacific Northwest	24.7	34.9	60.4	143.
Central Pacific	50.0	60.2	69.1	47.
South Pacific	10.8	19.3	28.5	.4*
U. S.	300.3	558.9	888.4	1100.

* Little or no excess supply expected available after 1980.
** No excess after 2000.

SOURCE: U. S. Senate Select Committee on National Water Resources, August 1960, Committee Print No. 32.

Table 1.4--Present vs. Required Minimum Storage (1000 acre feet)

River Basins	1954 Present	1980 (add to 1954)	2000 (add to 1954)
New England	9.0	2.4	6.1
Delaware and Hudson	3.1	5.8	12.0
Chesapeake Bay	.9	4.3	14.5
Southeast	16.4	9.8	21.5
Eastern Great Lakes	.5	8.5	20.0
Western Great Lakes	1.2	34.0	50.0
Ohio	5.7	8.5	16.0
Cumberland	6.4	.3	.8
Tennessee	15.0	.1	.4
Upper Mississippi	4.3	5.8	17.0
Lower Mississippi	4.5	8.5	18.0
Upper Missouri	74.8	30.0*	30.0
Lower Missouri	1.2	2.3	4.9
Upper Arkansas	7.3	8.0	13.0
Lower Arkansas	26.8	9.6	14.6
Western Gulf	11.2	25.5	34.0
Upper Rio Grande and Pecos	3.3	@ 7.4*	7.4
Colorado	35.1	14.5*	14.5
Great Basin	4.1	6.5*	6.5
Pacific Northwest	28.9	10.8	14.7
Central Pacific	16.4	25.5	27.8
South Pacific	1.8	.6*	.6
U.S.	278.0	+228.8	+344.0

* Little or no excess supply expected available after 1980.

SOURCE: U. S. Select Committee on National Water Resources, August 1960, Committee Print No. 32.

Table 1.5--Water Supply vs. Projected Uses

	East	West	Pacific N.W.
Max Dependable Flow that can be made available (bgd)	790.4	154.1	136.3
Depletions (bgd)			
1960	13.7	59.7	11.1
1980	24.3	68.7	13.5
2000	37.4	91.7	20.0
On-Site Uses (bgd)			
1980	35.3	34.5	.9
2000	48.0	47.5	1.3
Waste Dilution Flows (bgd)			
1980	251.5	51.9	28.9
2000	342.3	76.2	28.0

SOURCE: Landsberg, H. H., Fischman, L. L., Fisher, J. L., "Resources in America's Future - Patterns of Requirements and Availabilities," The Johns Hopkins Press, 1962.

Figure 1.1--Water Resource Regions

SOURCE: U. S. Senate Select Committee on National Water Resources, S. Res. 48, 86th Congress, "Water Requirements for Pollution Abatement," Committee Print 29, July 1960.

treatment requires smaller dilution flows, hence less investment in reservoirs. In Table 1.6 two programs [215] are outlined, each considered adequate to meet the future requirements. In the first program the maximum amount of waste is assumed to be treated so as to minimize the amount of dilution water required. In the second program the maximum storage of water is assumed, hence minimizing the need for treatment facilities.

In these programs the average cost of an additional acre-foot of surface storage varies between $37 and $66. The present average cost is estimated at $55 over all of the reservoirs constructed by the Army Corps of Engineers.

Program A Minimum Storage - Maximum Treatment

Program B Maximum Storage - Minimum Treatment

Table 1.6--Cost of Future Water Development Programs

	1980		2000	
	A	B	A	B
Capital Cost of Additional Storage (Billion)				
1954-1980, 1954-2000	8.4	38.5	114.3	45.2
Capital Cost of Treatment Facilities (Billions				
1954-1980, 1954-2000	54.2	35.8	92.8	73.1
Total Capital Costs (Billions)	62.6	74.3	107.1	113.3
Total Annual Costs (Billions)	2.7	3.3	4.7	5.2

SOURCE: U. S. Senate Select Committee on National Water Resources, August, 1960, Committee Print No. 32.

1.4 SOME APPROACHES TO WATER SUPPLY PROBLEMS

After collecting and presenting the estimates of supply and demand in the United States to the year 2000, Nathaniel Wollman, the author of the first comprehensive study of the situation, concluded before the U. S. Senate Select Committee on Water Resources [215] that for five western regions of the United States

> "unless new technologies of water use are discovered or unless supplies are augmented by importation, weather modification of run-off or desalinization, projected patterns of (water) use are impossible of fulfillment."

The regions involved are the Upper Missouri, Rio Grande, Colorado, Great Basin and South Pacific. They had a 1960 population of 24.4 million which is expected to increase to 51.8 million by the year 2000.

All of the new but non-nuclear approaches suggested for providing an adequate supply of water to these regions, as well as the existing approaches to meet the nation's water needs, fall into four general categories.

1.4.1 Storage of Run-Off for Later Use

a. Surface storage. The employment of surface reservoirs is the major means of capturing and storing water for later use. In 1954 there was 277.9 million acre-feet of storage in the United States. In the East this averaged .6 acre-feet per person and in the West 4.2 acre-feet per person. In the five critical western regions it is estimated that 60,000,000 acre-feet of additional storage will be

needed by 1980. This would provide an average of 9.3 acre-feet per person in those areas.

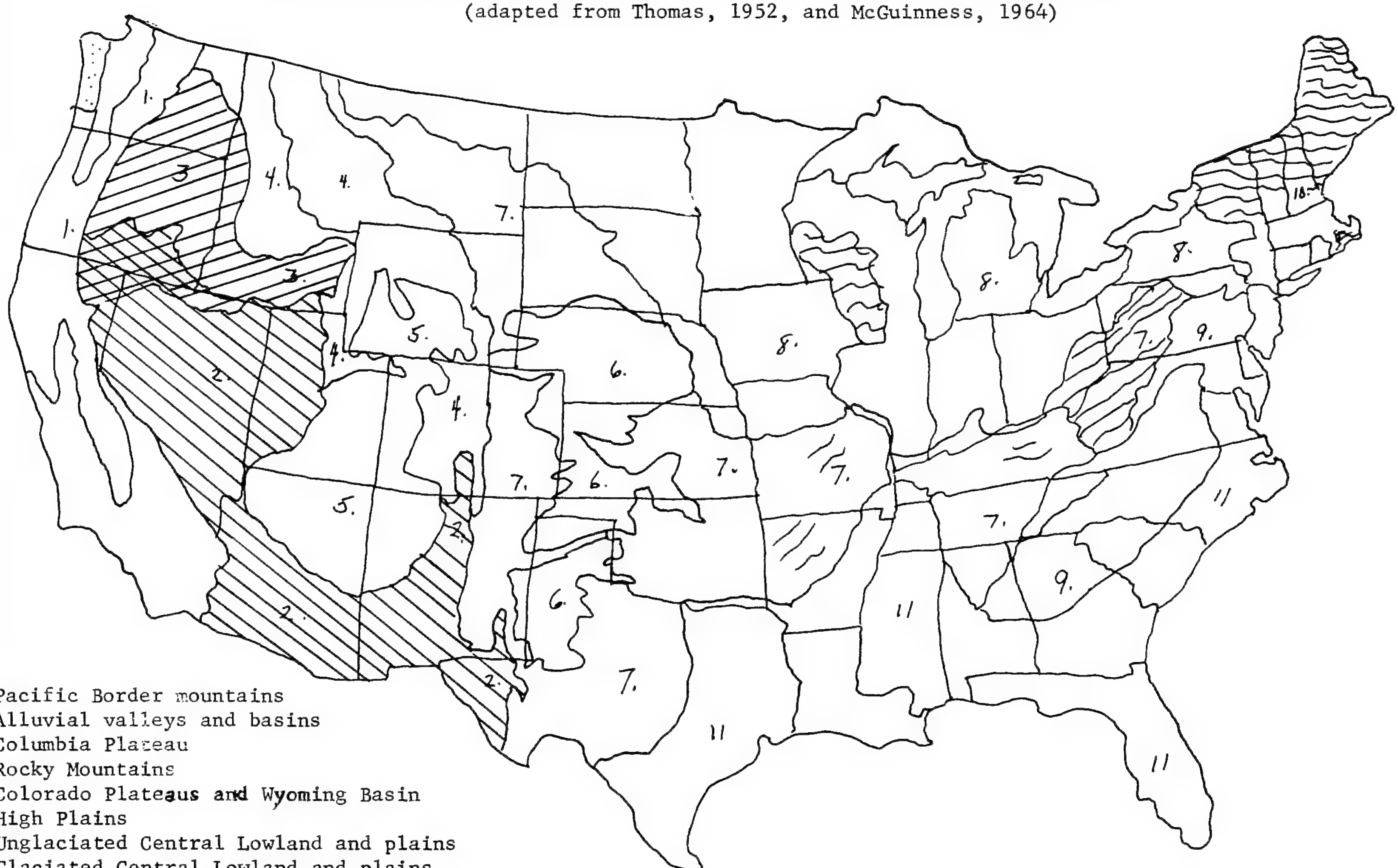
b. Underground storage. Natural aquifers underlie many regions of the United States. Figure 1.2 indicates eleven ground-water regions or provinces in the continental United States [225]. It is apparent that because of the large extent of most of these provinces that they not only serve as a storage system for water but also as a distribution system. The withdrawal of water from this source averages about 18 per cent of all withdrawals. In 1960, for example, of the 323 bgd withdrawn, 59 bgd is estimated [228] to have been withdrawn from wells tapping aquifer formations.

1.4.2 Water Upgrading

a. Waste treatment. Waste water which is treated requires far less fresh dilution water and permits more rapid re-cycle of the water back into the withdrawal channels. It is estimated that an expenditure of the order of 2.0 billion dollars annually for construction and operation of new and improved waste treatment facilities will be required by the United States in the next 50 years.

b. Water purification. Water below the acceptable quality level for municipal use can often be economically purified. Many installations exist for adding chlorine, and recently fluorides to the drinking water supply. Other processes are also performed, such as filtration, aeration and sedimentation which serve to upgrade the quality of water. The distinction between purification and waste treatment of water is that in the former the processes are performed prior to usage, and in the latter after usage. For users of a common-flow the extent of

Figure 1.2--Ground-water provinces of the conterminous United States
(adapted from Thomas, 1952, and McGuinness, 1964)



1. Pacific Border mountains
2. Alluvial valleys and basins
3. Columbia Plateau
4. Rocky Mountains
5. Colorado Plateaus and Wyoming Basin
6. High Plains
7. Unglaciated Central Lowland and plains
8. Glaciated Central Lowland and plains
9. Unglaciated Appalachia
10. Glaciated Appalachia
11. Atlantic and Gulf Coastal Plain

SOURCE: Piper, A. M., Stead, F. W., "Potential Applications of Nuclear Explosives in Development and Management of Water Resources - Principles," U. S. Department of Interior, TE1-857, March, 1965.

waste treatment by one party affects the degree of purification required by other parties. Arrangements among jointly affected users transcends political boundaries and in the future greater emphasis on regional resource development will become necessary [226].

1.4.3 Exploitation of New Supplies

a. Desalinization of sea water or brackish water. This appears to be feasible only for areas near sources of sea or brackish water, such as the South Pacific river basin. Even if the desalinization cost is kept in the \$.20-\$.30 per 1000 gallon range, the transportation of this water via pipelines could add about \$.08 per 1000 gallons per 100 miles [216]. This cost is too high for the irrigation water needs of the western states. Irrigation water commonly costs less than \$10 per acre-foot or under \$.03 per 1000 gallons.

Municipal water in the western regions and particularly in the South Pacific basin is much more expensive, and costs between \$10 to \$75 per acre-foot, or \$.03 to \$.20 per 1000 gallons (1960).

It should be noted that large scale use of desalinization by coastal municipalities will decrease the need for high quality inland water sources, hence freeing these for diversion elsewhere.

b. Weather modification. Localized success with cloud seeding to produce rain has been reported [218], but most evidence indicates that this will alter the distribution of water and not appreciably increase its supply since clouds of a rain-bearing nature and under rain-producing conditions seem to be a prerequisite for success. Climate control on a larger scale has numerous political problems as well as international interactions and has an uncertain future.

c. Deep drilling of wells. New water supplies may become available in some regions by tapping very deep aquifers (below 1000 feet). The expense of drilling such deep wells and the associated pumping costs will limit this method to municipalities with critical water needs.

d. River diversion. When rivers run too quickly to the sea usable water is lost. This water can often be diverted to new channels and the direction of the flow changed. Generally, river diversion proposals involve very large earth moving and construction operations. The NAWAPA project [85], one of the largest construction projects ever envisioned, would divert water from Alaska and Northern Canada into the Rocky Mountain Trench in Canada (a depression 500 miles long) from where it would be distributed as far south as Mexico and as far east as the Great Lakes. The cost is estimated [85] to be in excess of 100 billion dollars over a 20-year period, which is comparable in scale to the NASA space program. Seventy-eight million acre-feet of water could eventually be diverted to the United States plus considerable hydro-electric power, sale of the latter offsetting part of the project cost.

1.4.4 Conservation of Water

a. Evaporation suppression. A considerable loss of usable water occurs from evaporation of water already impounded in reservoirs. In arid regions where due to the sporadic rainfall, water has to be stored longer, this is an especially acute problem. Deeper reservoirs exposing less surface area would reduce this loss. Underground storage would almost entirely eliminate it. Chemical means for reducing evaporation by spreading a thin mono-molecular film over the water surface in reservoirs has had limited success.

b. Vegetative management. Some ideas in this area are the replacement of deep rooted grasses by shallow ones to permit more water run-off; selective application of irrigation water during the crop growth cycle; and the removal of non-beneficial vegetation along irrigation canals. In a project [219] along the Rio Grande River in Texas, a dyked floodway 600 to 1400 feet wide and 217 miles long has been cleared of phreatophytes (ground water using plants). It is estimated that 50,000 acre-feet of water will be saved a year. In the Caballo Reservoir area of New Mexico, 5,300 acres of salt cedars and mesquite has been removed saving 14,000 acre-feet of water per year. The cost was about $60,000 and the annual maintenance cost is about $8 per acre.

c. Planned land use. A gallon of water used for municipal or industrial use supports a much larger amount of economic activity than one used for agriculture. In a study made in New Mexico [227] it was estimated that an acre-foot of water used for municipal or industrial use stimulated $3000 of economic product compared to $45 for agricultural use.

A relatively small diversion of water from agriculture could support a considerable increase in population if alternate sources of food become available.

1.4.5 Use of Nuclear Explosives

Nuclear explosives have been suggested for a number of applications in the water resource field. In general, it is the earth-moving or rock crushing power of a controlled nuclear explosion which is the salient feature of the application. In some approaches to water supply management, an economic advantage may be obtained by harnessing

this power. At the present time it appears that the proposals which are most attractive are those which accomplish something unattainable or extremely difficult with conventional technology. An example of the latter would be the construction of a surface reservoir in a flat semi-arid region, which is without natural sites. A crater on the land surface produced as the after effect of a nuclear explosion could conceivably alter an unlikely approach into a very practical one in this particular geographical situation. The nuclear explosions which are contained by deep underground burial offer a range of possibilities generally outside the realm of conventional technology. These possibilities involve the flow and storage of water underground and proposals along these lines envision the connection of separated aquifers systems, undercutting of perched water bodies, creation of new sites for recharging aquifers, and the construction of underground water storage facilities.

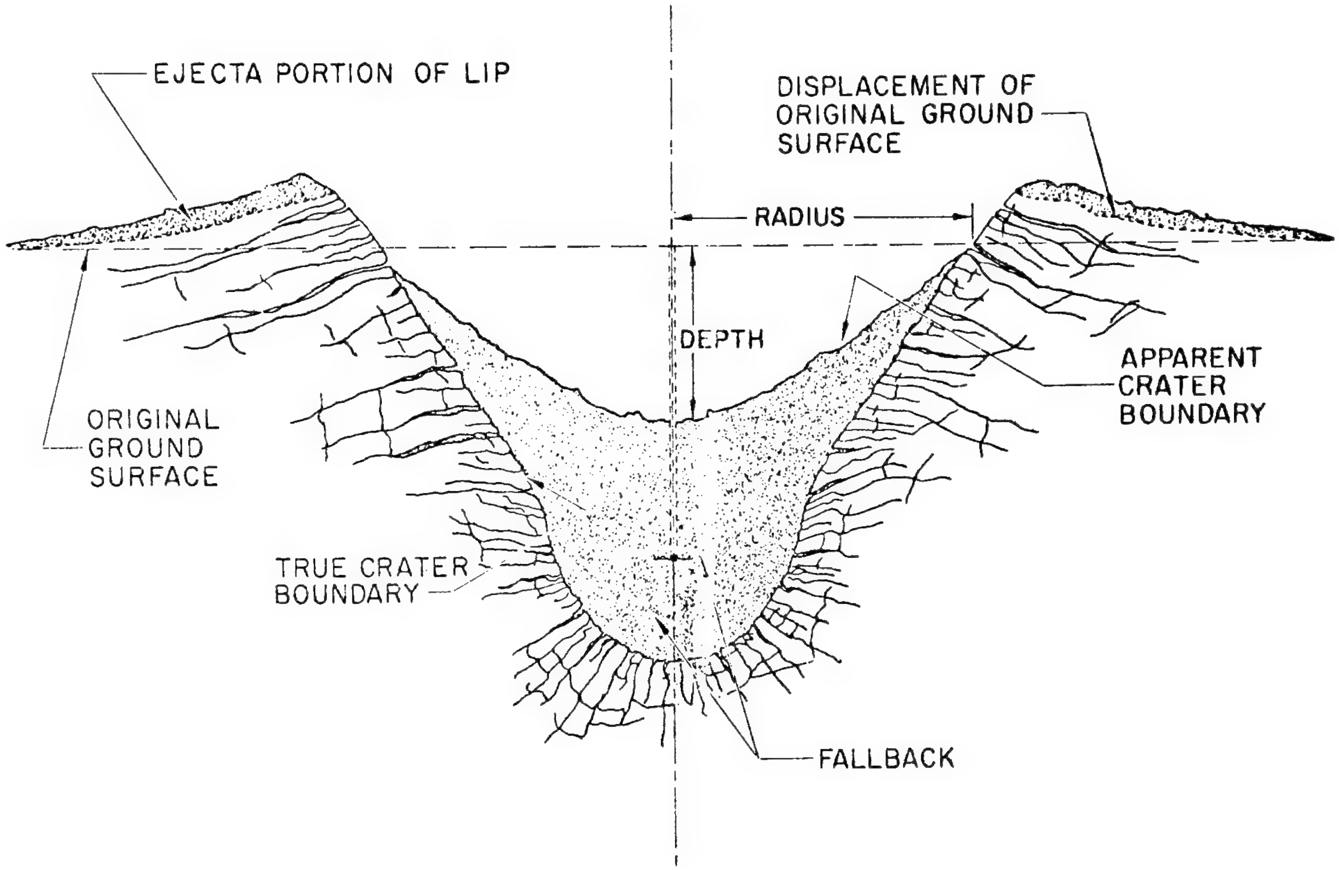
Nuclear effects occur on so large a scale that the alteration of the natural water environment by this means can be called geo-engineering. Three identifiable aftereffects of a nuclear explosion are applicable to geo-engineering. They are discussed in the following section.

1.5 USEFUL STRUCTURES CREATED BY NUCLEAR EXPLOSIVES

1.5.1 Throw-out Craters

A throwout crater is created from an explosion detonated underground, but at a relatively shallow depth. The explosive force lifts the overlaying earth high enough so that the "fire ball" is no longer contained. The explosion vents to the atmosphere and considerable rubble is thrown from the site leaving a large parabolic shaped crater in the

Figure 1.3--Cross section of a typical crater in rock



SOURCE: Nordyke, Milo D., "Cratering Experience with Chemical and Nuclear Explosives," Lawrence Radiation Laboratory, Livermore, page 52.

ground (Figure 1.3). The dimensions of the crater can be varied for a given kiloton yield by changing the depth of burial of the device. Some of the rubble falls back into the cavity forming an "apparent crater." That is the surface depression visible to the eye. The fallback material, being broken and uncompacted, is more permeable to water than the surrounding earth. Under the detonation point there is a zone of material which, having experienced the full shock effect, may be less permeable than before the blast if it is an alluvial-type material, or more permeable if it is hard rock due to the tendency of rock to fracture under pressure. Since the ratio of crater diameter to depth can be varied some control is possible between the crater wall area to bottom area.

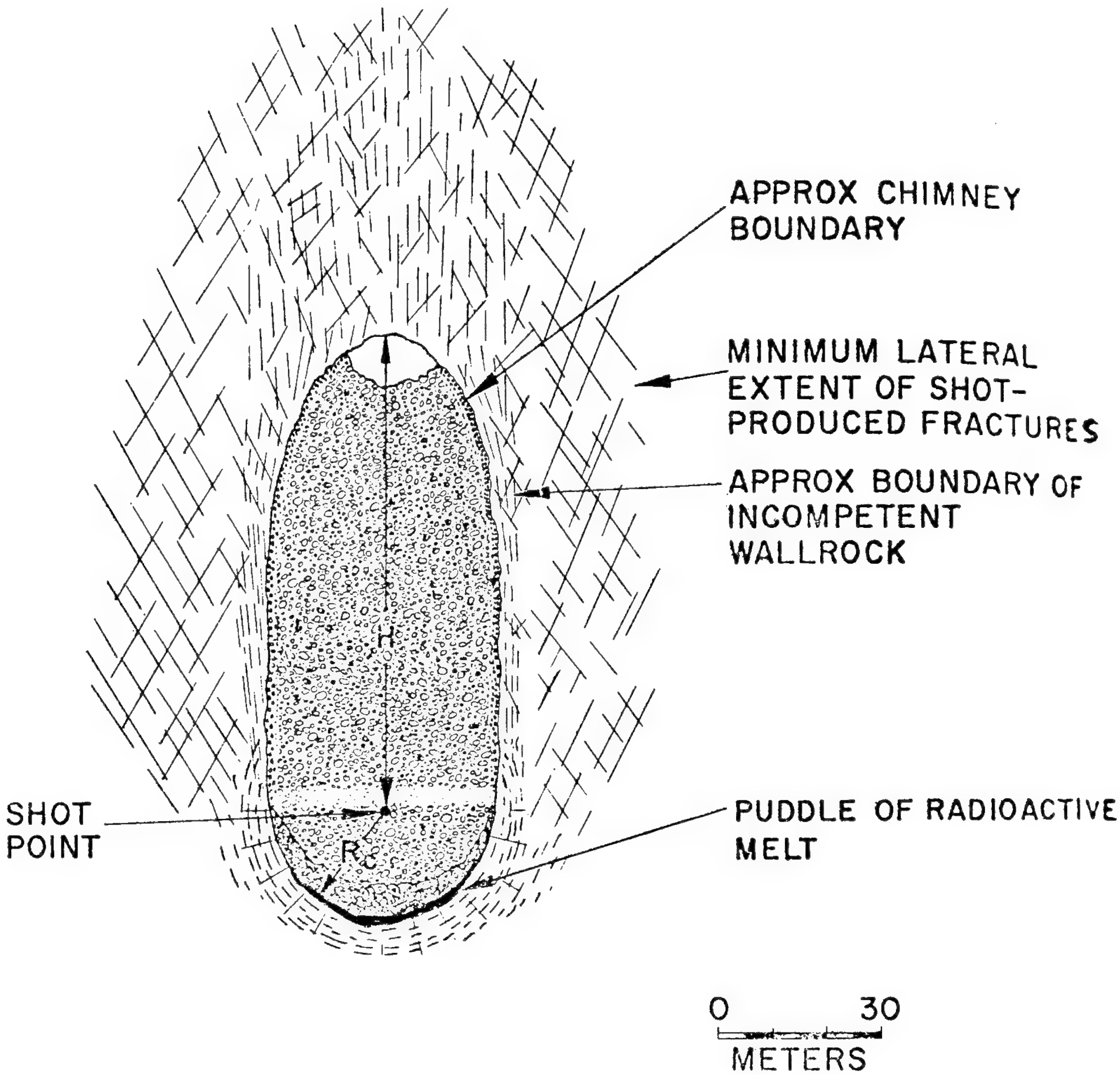
1.5.2 Collapse Chimneys

When the depth of burial of the nuclear device is sufficient, the explosive force can be completely contained underground. The "fire ball" vaporizes some of the surrounding material which then expands and creates an underground cavity or void space. In most cases the weight of overlying rock soon crumbles the roof of the void chamber and a column or "chimney" is created by the successively falling layers (Figure 1.4). The material in the chimney suffers some compaction after collapsing but the initial amount of void space created by the blast just after detonation is distributed in this broken rock. This occurs because the falling roof material bulks, and the extension of the chimney upwards stops when the bulking rubble has distributed the cavity volume. Hence, this chimney should be more water permeable than the undisturbed surrounding material in spite of the compaction.

1.5.3 Subsidence Craters

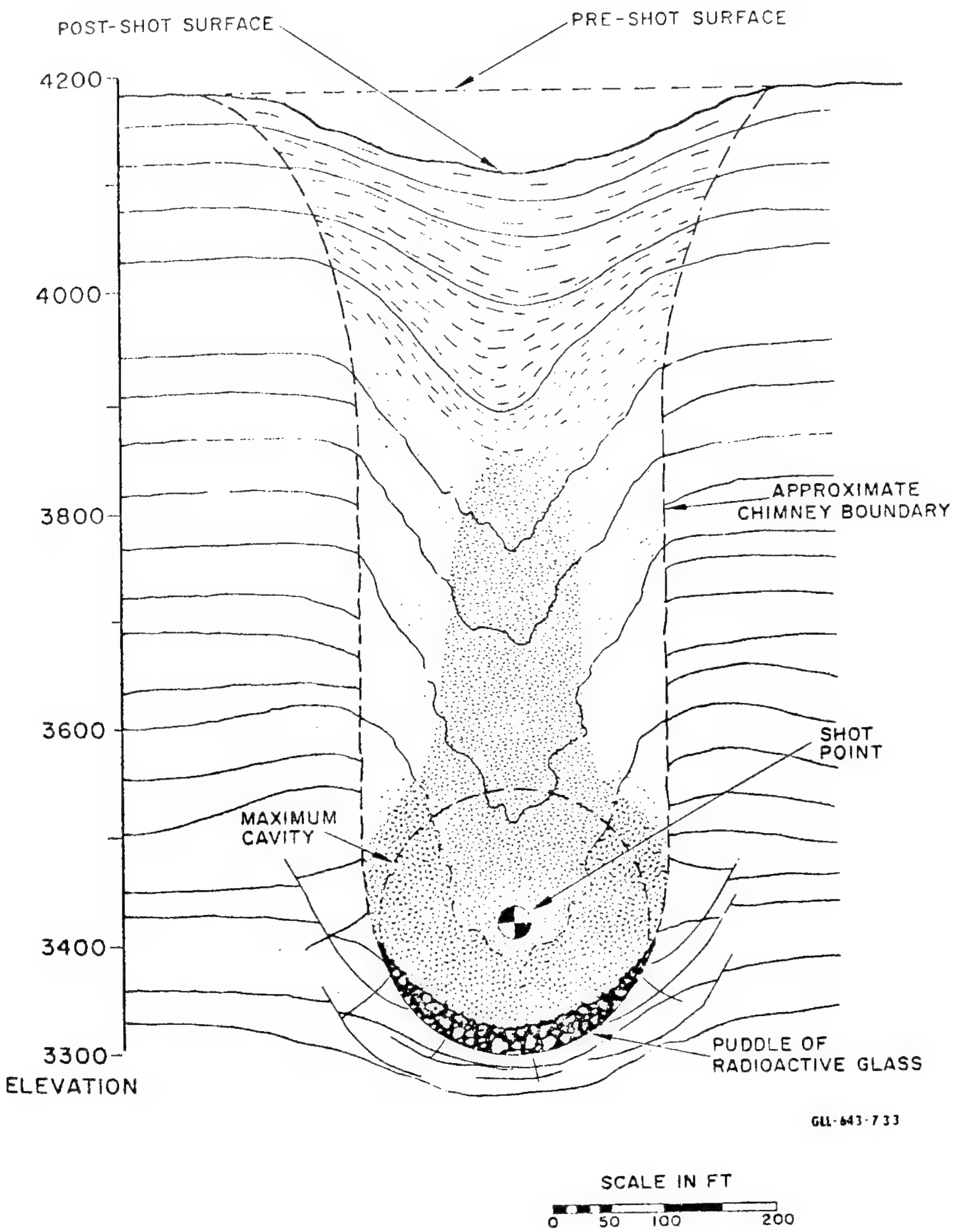
When a deeply buried nuclear explosion creates a collapse chimney it is possible that the column of broken material which extends upwards

Figure 1.4--Schematic cross section of a hard rock medium after a contained nuclear explosion.



SOURCE: Kruger, Paul, "Nuclear Civil Engineering," Department of Civil Engineering, Stanford University, September, 1966.

Figure 1.5--Schematic cross section of a typical crater in alluvium.



SOURCE: Nordyke, M. D., "Cratering Experience with Chemical and Nuclear Explosives," Lawrence Radiation Laboratory, Livermore, GLL-643-733.

from the blast point terminates only when the land surface is reached. Since the surface earth has fallen into the chimney zone of collapse a crater called a subsidence crater is formed. The permeability of the bottom of the crater would vary depending upon the type of material (Figure 1.5).

1.6 SUGGESTED PLOWSHARE APPLICATIONS

The three structures resulting from a nuclear explosion have been proposed to produce changes in the natural environment of water. These suggestions are grouped here under the four approaches to the water supply problem.

1.6.1 Surface Storage

On July 6, 1962, a nuclear device [187] with 100 kilotons of TNT equivalents in energy was detonated at a depth of 635 feet in the dry alluvium of the Nevada Test Site. The explosion (called Project Sedan) produced a crater 1,200 feet in diameter and 320 feet deep. The storage capacity of this crater if filled with water would be about 4,000 acre-feet. The cost of the device, its arming and firing [1] is \$460,000, or \$154.0 per acre-foot. A one megaton device would produce a crater holding 10,000 acre-feet at a cost of \$750,000 or \$57.0 per acre-foot. With the site preparation, safety, and other project costs added these unit costs could double to \$308 and \$114 per acre-foot respectively.

Reservoir construction costs by conventional means are not wholly comparable because reservoirs are usually built at sites where the natural land topography is favorable. Hence, the capital costs are spread over a much larger storage capacity, some of it naturally occurring. In California, smaller dams for reservoir purposes have been constructed by the Santa Clara Water Conservation District

(South Pacific Region) and these have ranged in cost between $150 and $1,100 per acre-foot. Figure 1.6 illustrates the cost comparison for these smaller "vest pocket" dams [1]. It would appear that in selected circumstances a nuclear crater could be economically justified for water storage use. In addition, two other features of this technology are significant. First, craters can be constructed in open country without the benefit of natural sites, and second, the ratio of exposed surface area to volume can be varied to produce deeper reservoirs. This would retard the rate of water evaporation so that for the same usable water yield a larger conventional shallow reservoir would be necessary. The median depth of reservoirs in the United States is about 25 feet, and in the South Pacific region 44 feet, in contrast to a nuclear crater which may be several hundred feet deep.

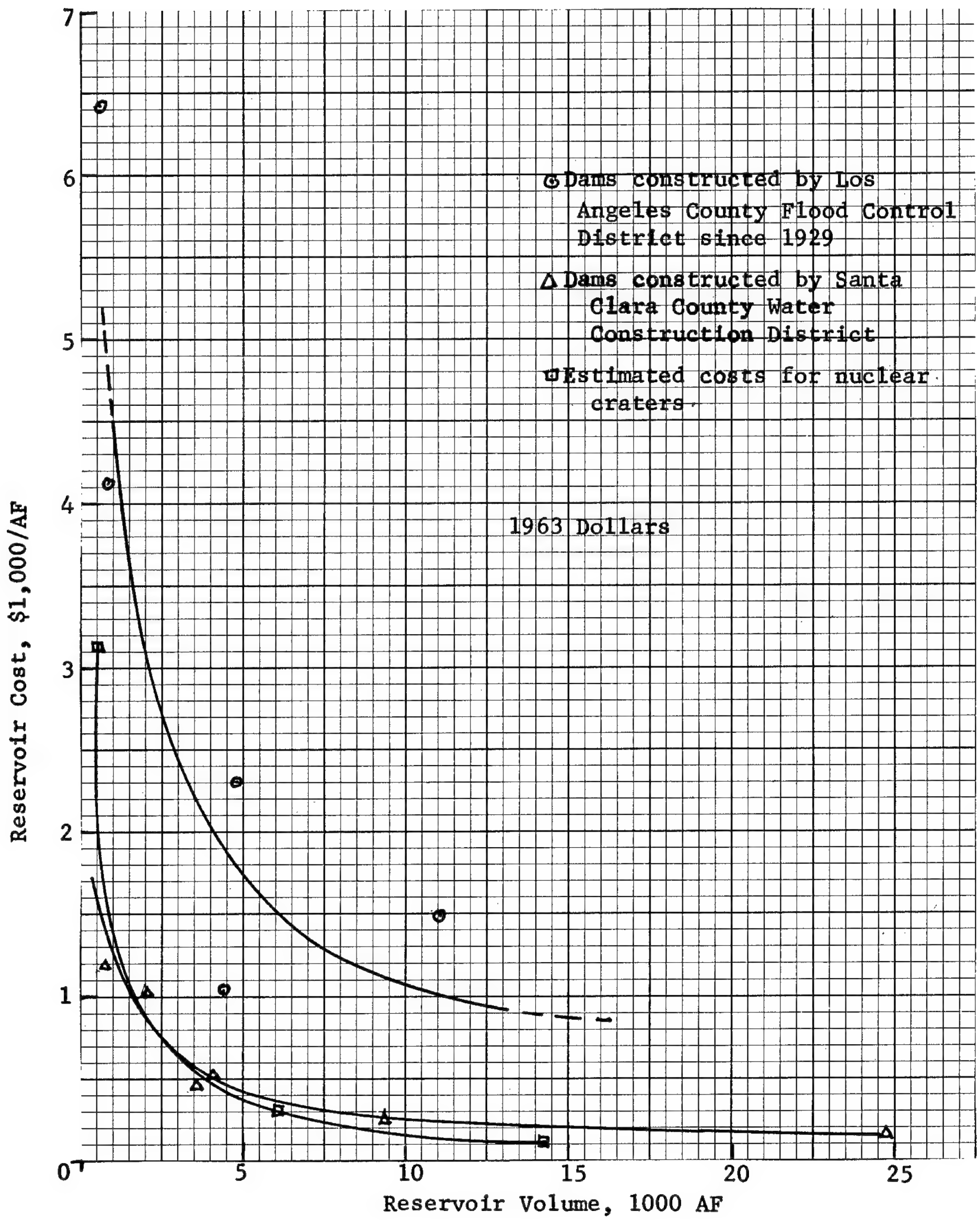
This may not be entirely desirable because any storage below the hydraulic water table must be pumped out. An additional consideration with nuclear craters is the need for works to enable the crater to be filled and withdrawn [75].

The uses to which crater storage space could be put depends upon the choice of sites for their location.

a. They can be used off channel of regular stream flow to catch flood run-off which would be added to the usable supply at a later time [236]. A more economic prospect is the use of serially arranged craters (row charged) to excavate a channel for water conveyance to a natural off-river storage site.

b. They can be used in conjunction with hydro-electric installations since water can sometimes be profitably pumped to higher elevations (into a temporary reservoir) by using off-peak power. This storage water would be released for generating power during peak periods.

Figure 1.6--Unit Costs of Selected Reservoirs in California and of Nuclear Craters



c. Run-off patterns can be changed for improved disposal of drainage waters by channeling the water into strategically located craters. This may be useful near major transportation lines which are susceptible to "washout."

d. Popular types of recreation often require open bodies of water for boating, fishing, swimming, etc. A very large future demand has been projected for new outdoor facilities.

In many areas most of the natural sites will have been developed by the 1970's and some artificially produced lakes may be the only means of satisfying the demand thereafter. A series of craters of different sizes plus connecting channels either on or off the main stream flow path could be designed into an attractively useful recreation area, which would pay for itself through user fees.

The possibility of using subsidence craters instead of throw-out craters to limit the release of airborne radioactivity exists in some applications, but a considerably smaller surface volume is created for the same yield device. This may range from 1/8 to 1/5 optimum throw-out crater volume. A small portion of the radioactivity can still vent to the atmosphere depending upon the speed with which the collapse chimney forms, but nevertheless subsidence craters essentially eliminate airborne radioactivity as an obstacle to cratering applications.

1.6.2 Underground Storage

For the past 60 years, since information has been collected, the use of groundwater has averaged about 18 per cent of total withdrawals.

It would appear that use of groundwater instead of surface water is better suited for solution of many of the problems of future water supply. The advantages are [222]:

1. Lower evaporation loss of water stored underground.

2. Lower cost of distribution since the wells can be located closer to the demand.

3. Provision of a measure of safety in case of earthquakes, dam failures, severed aqueducts, etc.

4. Less purification required since percolation through the earth filters the water.

Table 1.7--Estimated Groundwater Use (bgd)

Year	Total	Groundwater	Per cent
1900	40.19	7.28	18.1
1910	66.44	11.68	17.6
1920	91.54	15.78	17.2
1930	110.50	18.18	16.5
1940	136.43	22.56	16.6
1950	202.70	35.19	17.4
1960	322.90	58.17	18.0

SOURCE: Department of Commerce, Business & Defense Service Administration, "Water Use in the U.S., 1900-1980."

Three of the problems preventing wider use of groundwater are subject to solution by Plowshare proposals.

The first and major problem is the ability to recharge the groundwater. Replenishment normally comes from rainfall and stream flow which has infiltrated permeable soils. Natural recharging may be inadequate both because of the lack of recharge sites such as stream beds, basins, pits, wells, etc., which have permeable connections to the underlying aquifers, and because of the slow rate at which water travels in the ground. In areas where heavy drafts have been made on the groundwater without compensating recharge the regional water tables have fallen. Since the height of the water table determines the static level water will reach in a well, a lowered water table means that the water has to be pumped a greater distance to the surface. The pumping cost is the major cost component in groundwater systems. In some areas of the United States a more serious consequence of depleting groundwater supplies is the encroachment of saline water into the fresh water aquifers. In Long Island, New York, a coastal area jutting into the Atlantic Ocean, this problem is so serious that there are over 1,100 wells in operation which return used water to the aquifers in an attempt to maintain a higher pressure gradient in them. A similar situation exists in the coastal regions of California.

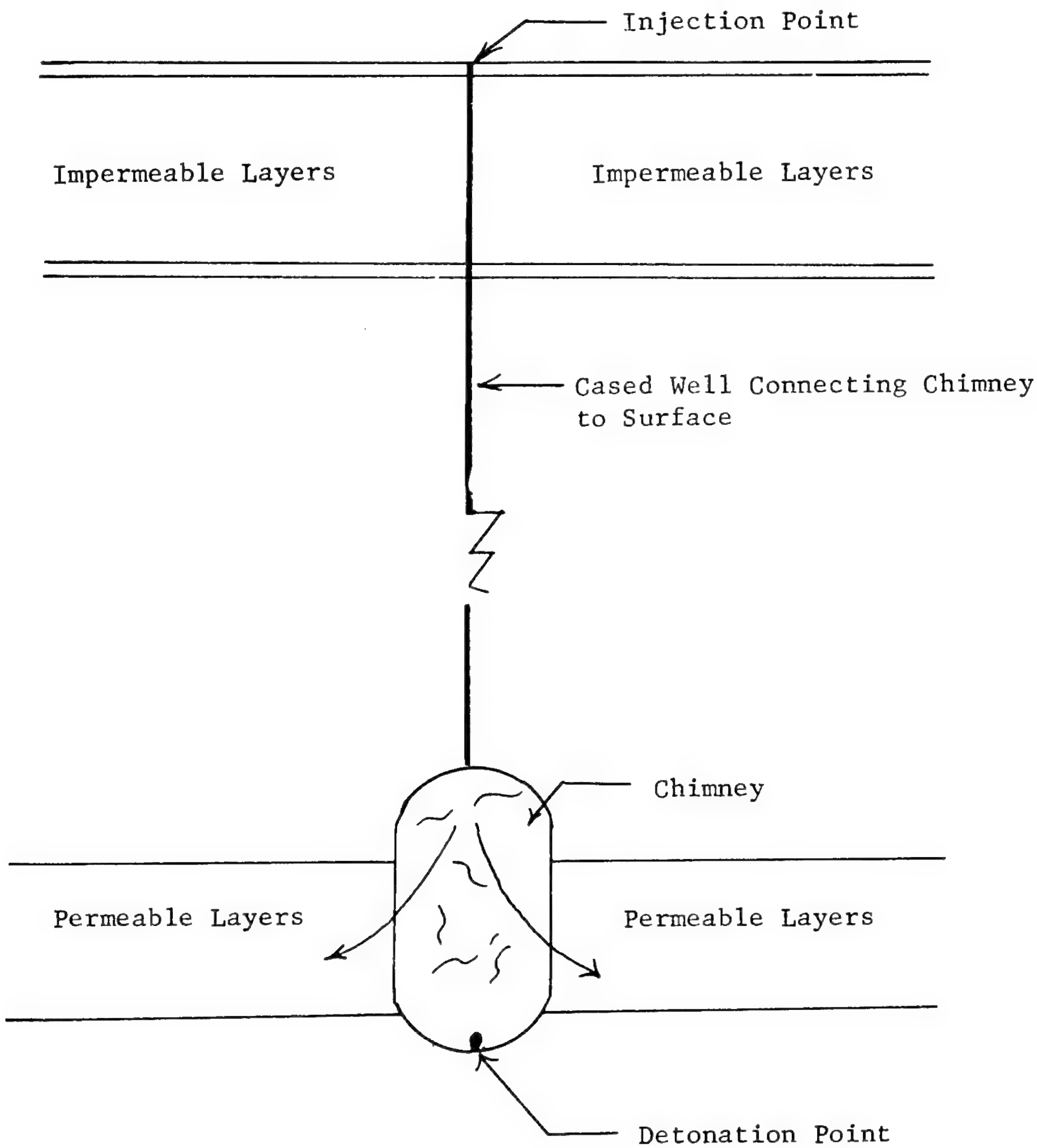
Three different applications of nuclear explosives can be made to produce new aquifer recharge sites. A throw-out crater which has permeable sides can be used to catch runoff and transmit it underground. A subsidence crater can be used, in which case the permeable bottom of the crater would transmit the water through the rubble chimney. A contained chimney can also be used for recharge purposes. It can be located beneath an impermeable overlayer and a cased well drilled

into it to conduct the water underground (Figure 1.7). In this configuration the rubble chimney acts like a gigantic injection well.

Numerous aquifer recharge sites have been suggested in each of the 11 groundwater provinces by local officers of the U. S. Geological Survey. In a typical application [225] in the High Plains province (Figure 1.2) the area is underlayed by the Ogallala formation, which is an extensive aquifer of very large water storage capacity. It can yield as much as 1,000 gallons of water per minute in single wells. In Texas, New Mexico and Oklahoma, this formation has been tapped by tens of thousands of wells mainly for irrigation.

Infiltration of rainwater is impeded by "caliche" formations over the aquifer and it is probable that recharge to the groundwater occurs only during exceptionally wet years. A subsidence crater formed from a 10 kiloton explosion would yield about 100 acre-feet of storage space. If the runoff could be held long enough before being depleted by evaporation, recharge to the aquifer would occur. Several thousand such explosions would be necessary to create any measurable effect. Since the size of each explosion (10 kilotons) is small in a nuclear sense,it is possible that appropriate sites could be found. If we assume that each crater could recharge 1,000 acre-feet per year, then 100 detonations would be necessary to recharge 1,000,000 acre-feet/year. The cost of the nuclear device at the present published rates of the Atomic Energy Commission of $350,000 per 10 kiloton device would be 350 million dollars. Volume discounts have not been published by the AEC but this presumably would reduce the cost

Figure 1.7--Nuclear Chimney Aquifer Recharge Site



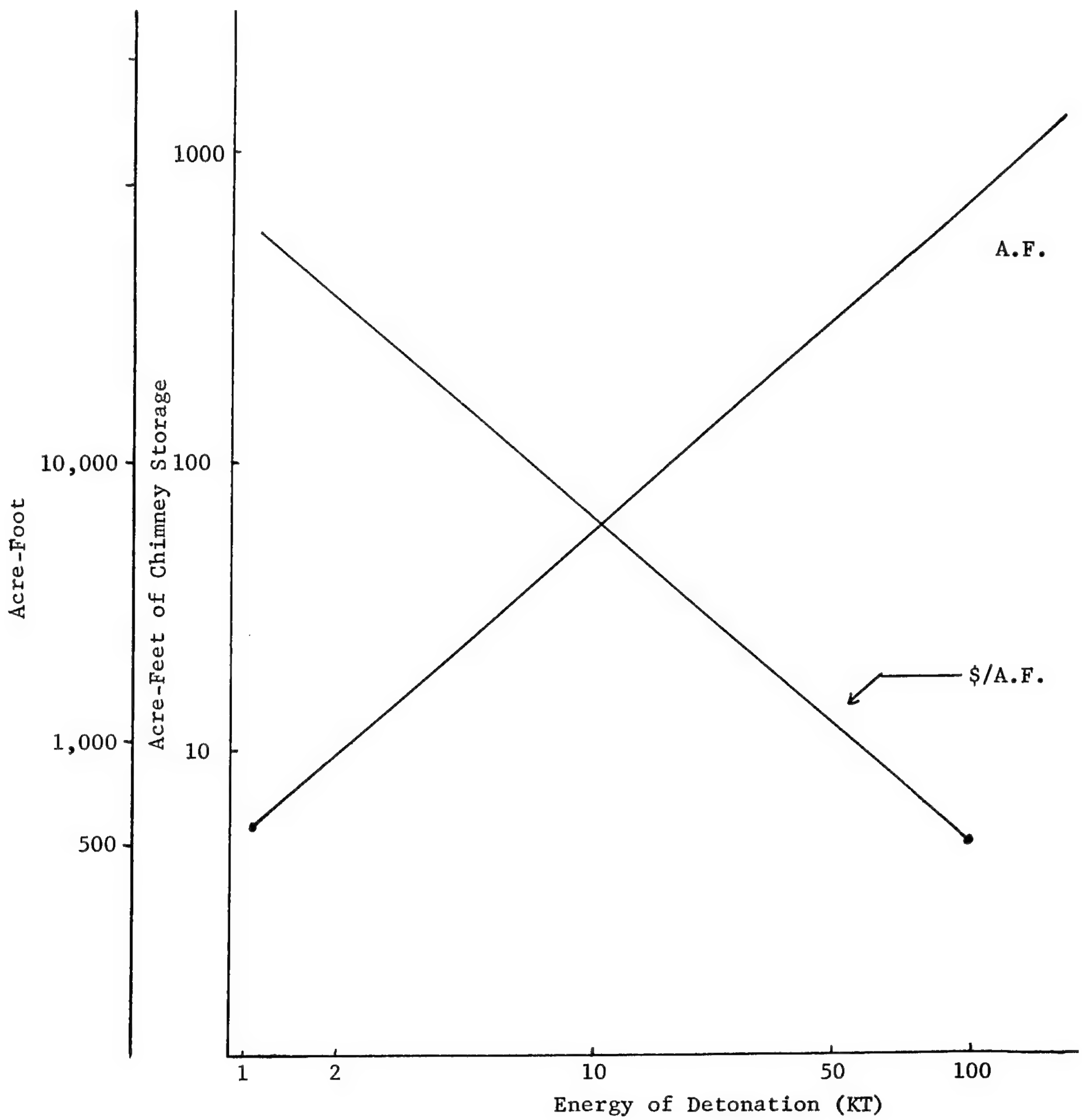
significantly. Since the degree of economic activity stimulated by an acre-foot of water is 45 dollars per AF for agricultural purposes (New Mexico), this implies a 45 million dollar per year benefit.

The second difficulty preventing greater groundwater use is the occurrence of natural faults in the earth which separate aquifer systems. A typical case [225] occurs in the Unglaciated Central Lowland province (Figure 1.2) at Miami, Oklahoma. When usage began about 1900, the water pressure was so strong that the wells flowed on the land surface without pumping. By 1960 the pressure head had dropped so that pumping levels were 750 feet below the surface. A fault separates the withdrawal area from the main recharge area. Several nuclear rubble chimneys could breach this fault and induce an increase in head between the two areas (see Figure 1. 8).

A related use for a rubble chimney has been proposed where perched water bodies lie above, but separated by impermeable rock, from a lower aquifer strata. In this case the detonation would be sufficiently below the perched water body so that the rubble chimney would just extend upwards to it. The rubble chimney would act like a large pipe and if the water table of the aquifer is below that of the perched body, then an increase in aquifer pressure results. This application would be useful both for recharging an aquifer and re-pressurizing it.

The third problem limiting groundwater use is the absence of usable aquifers in some areas. A nuclear rubble chimney can serve as underground storage when the surrounding strata is impermeable. A ten kiloton contained device, for example, produces 60

Figure 1.8--Storage Space in Nuclear Rubble Chimney



acre-feet of usable void space (20 million gallons). A 100 kiloton has been suggested [225] for the area near Ashland, Oregon. The rubble chimney would hold 600 acre-feet or almost 60 per cent of the community's need. The cost of the device would be $460,000, or $770 per acre-foot. Recharge would be from normal stream flow in wet months. Comparable surface reservoir storage of 1,000 acre-feet could cost as much as $400,000 if an appropriate site is available.

1.6.3 Waste Treatment

Waste treatment per se is not the subject of any Plowshare proposal but waste disposal which is closely related has a number of possibilities.

Surface craters can be used to store highly contaminating waste effluents. Disposal can be hastened until adequate dilution water becomes available. In areas where natural stream flow levels fluctuate widely, this could be a uniquely useful control device because in order to maintain adequate stream flows for year-round dilution purposes extensive reservoir systems are necessary. A gross view of the importance of more effective waste disposal can be obtained by assuming the utilization of temporary waste storage equivalent in its average effect to increasing the degree of treatment. In New England, for example, an increase in waste treatment from 90 per cent to 95 per cent saves 12 bgd in dilution flow or about 3 million acre-feet of reservoir storage, the latter being used to guarantee the daily flow.

Contained nuclear chimneys can also be used for storage of waste effluents. In one case the storage can be permanent,

the intention being to isolate the wastes from the environment for a long period of time. Radioactive substances can be stored in this way. Generally, a very deep detonation is required to insure that the chimney is located below the prevailing regional water table. In this way the wastes would be prevented from gradually infiltrating the groundwater supplies.

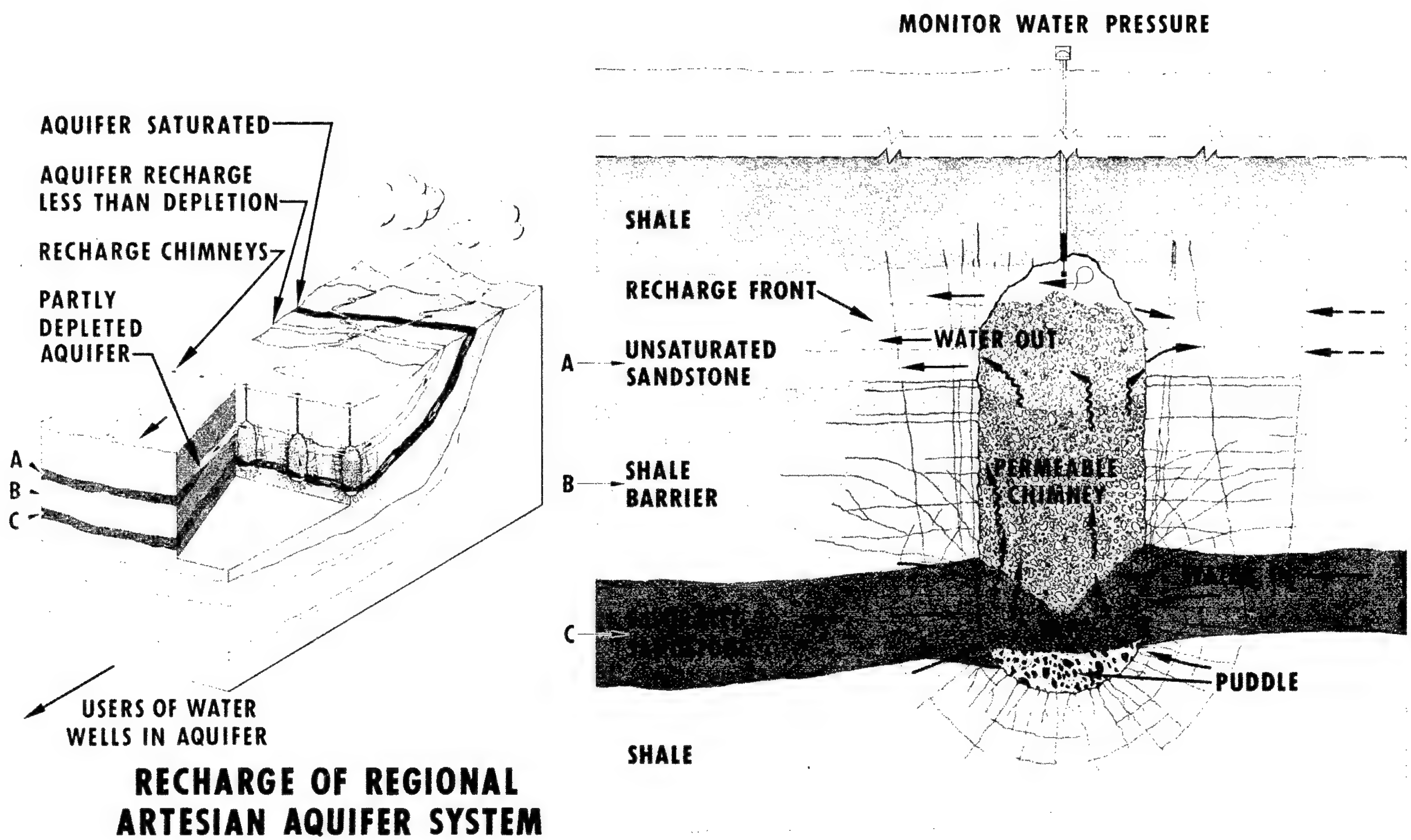
When the chimney is not below the water table the water flowing outwards is filtered by the surrounding medium and could be purified enough to safely augment the groundwater supplies.

One of the problems of a deeply buried nuclear detonation is the cost of the original emplacement hole, and the post shot well bore. An 18 inch diameter hole, 4200 feet deep, (for Project Gasbuggy) is being estimated at $307,000 or $73 per foot. A 36 inch diameter hole could cost [57a] between $100 and $300 per foot. Emplacement at 1500 feet would then cost between $150,000 and $450,000. The charge for a 50 kiloton device is $430,000 (producing about 100 million gallons of storage space). With site preparation and safety cost the total expense would be about one million dollars or $10 per 1000 gallons. Treatment cost for a corresponding amount of waste would be about $2 per 1000 gallons so that permanent storage in a nuclear rubble column would be about five times more expensive than treatment.

Current economics of this proposal do not seem to be attractive enough to stimulate municipal or industrial interest unless:

Figure 1.9

WATER RESOURCES MANAGEMENT



SOURCE: LRL-Livermore, Graphic Arts, Neg. No. GLC-665-3749, PNE-614.

a. The chemical nature of the wastes prevents their effective treatment.

b. Adequate dilution water, even after treatment is unavailable.

c. Other disposal sites such as the Ocean are too far away to warrant the transportation of the wastes.

1.6.4 Deep Wells

A nuclear rubble chimney could act as a collecting chamber within an aquifer strata or across several strata. A well drilled into the chimney would in effect have its diameter enlarged. Since the rate of water removed from a well depends upon the rate that it collects in the well bore a much larger and more dependable yield can be obtained. This feature would be attractive in areas where many individual wells serve local needs. One large dependable facility could serve the entire community. At Eureka, Nevada, a town of 1,000 people, a nuclear rubble chimney besides being a big well would serve as an underground storage reservoir [225]. A 20 kiloton device detonated at a depth of 1,000 feet could create a storage for 57 million gallons which is about a year's requirement of the community. The cost would be about $.20 per 1,000 gallons plus pumping and distribution costs.

1.7 SUMMARY AND CONCLUSIONS

On a national scale the United States is endowed with ample water resources. But in selected regional situations water shortages appear imminent as the population increases. By the end of the century eight of the 22 river basins in the United States may not have local supplies of clean water sufficient to support further development in the currently projected patterns. Four avenues have been suggested for solving these water shortage problems.

1. Increase the storage capacity of water for later use either on or beneath the land surface.

2. Upgrade more lower quality water through purification for immediate use, or through waste treatment to reduce the fresh water dilution needs.

3. Exploit new supplies, such as desalinization of sea water or through weather modification.

4. Conserve more water by reducing evaporation losses either in reservoirs through vegetative management, or by planning alternate uses of existing water supplies.

The geo-engineering possibilities of a new technology based upon high explosive energy released from a nuclear detonation has stimulated proposals for implementing projects in these four approaches to water resource management.

In the first approach it has been suggested that nuclear craters, throw-out or subsidence type, can be used as reservoirs for water storage. Their advantage occurs in situations where natural reservoir or dam sites do not exist, hence where conventional construction techniques would be expensive or impractical. The cost of such crater reservoirs appears to be within a feasible range.

Nuclear chimneys placed deep under the ground are also possible sites for water storage. In this case non-conventional construction methods are available for comparison, so a new field is opened for consideration. Its main advantage is that it permits storage sites to be built in water short areas, especially arid regions, which are not subject to the traditionally heavy evaporation losses of surface reservoirs.

In a similar context there is interest in the possibility of using nuclear produced structures in aquifer recharge projects. Storm water, for example, would be channeled to off-stream craters or to wells connec-

ted to buried nuclear chimneys where it would infiltrate the aquifer beds. To achieve any measurable effect with this proposal in a given project either a few very large, or numerous small detonations are required, hence aquifer recharge appears to be a subject area which could in the future be a major user of Plowshare energy.

In the field of water treatment, it has been suggested that deeply buried nuclear chimneys, beneath the water table, could be used for permanent storage of highly contaminating wastes, principally industrial wastes. If alternate means of disposal or treatment are available, this is an expensive application. However, under critical circumstances it offers a solution if the only other alternative is to stop production. Waste storage in this manner does not have as serious a problem of radioactivity control. It therefore appears to be an area which could be exploited at the present time, and certainly in the near future. Federally assisted pollution control projects could conceivably be broadened to include permanent underground burial.

Temporary waste effluent storage in surface craters has also been suggested as a means of spreading fresh dilution water requirements evenly over the seasons of the year. However, heavy waste effluent production is associated with more densely populated regions and it is doubtful if appropriate sites could be found for widescale use of craters.

New supplies of water could become available by tapping very deep aquifers. Even if nuclear chimneys participate in this task the cost of pumping water 1,000 to 3,000 feet to the surface will be a significant factor. An advantage of larger wells, in contrast to just deeper wells is their more dependable supply and economy of operation. Nuclear chimneys acting like enlarged well bores could permit consolidation of individual wells

into a community facility. Management and recharge of the aquifer would then be subject to more effective control and this may be a significant factor in semi-drought or water-short areas.

Other applications of Plowshare technology to the water resources field include the breaching of separated aquifer systems, and tapping of perched water bodies. These underground construction efforts would remedy defects of nature and help to increase the usable supply of water by re-pressurizing aquifers with larger quantities of purer water. Identifying situations where these methods will be useful and practical considering all relevant factors is a more complex issue than most applications. The scale of these projects will necessitate crossing political borders. Since the results of changing underground water patterns are not easily predictable a serious obstacle may exist in being able to obtain concurrence by all affected parties. However, many large undertakings in the water resource field are on a regional basis, such as by river basin, and this trend will undoubtedly continue to accelerate.

Finally, it has been suggested that nuclear craters can serve combined recreational and water supply needs. They can be used as lakes for boating, fishing, swimming, and related activities. Since the supply of these facilities is limited, and in great demand, it would be desirable to effect this combination. In fact, this may be an ideal way to inaugurate a Plowshare project in the water resource field as an attractively useful recreation area built with nuclear explosives could become a major tourist attraction.

As a concluding observation, it is an inescapable fact that all proposals of Plowshare uses for water resource management except deep waste burial hinge upon the satisfactory demonstration of radiological safety. Significant strides in this direction have been made since the first nuclear detonation in 1945. Experimentation subsequently has studiously avoided aquiferous regions. A phased series of test shots designed especially for these uses would be immensely important in clarifying the possibilities and timing of applications in water resource management.

Chapter 2

UNDERGROUND STORAGE OF NATURAL GAS IN NUCLEAR CAVITIES

2.1 INTRODUCTION

In 1959 Carlson [266] proposed at the Second Plowshare Symposium the use of nuclear explosives for oil and petroleum products storage cavities.* Since his proposal was made, a number of studies have been undertaken both within the Plowshare program, by the Bureau of Mines and by some of the gas companies, which make an appraisal of feasibility possible. The Columbia Gas System Service Corp. (Columbus, Ohio) has recently completed a feasibility study in connection with a possible experiment, Project Ketch, in which a 20 to 30 kiloton nuclear explosive emplaced at a depth of about 3,300 feet would be fired to produce a nuclear "chimney." The gas would be stored under pressure in the rubble-filled chimney together with the surrounding system of fractures, which are expected to have gas capacity of about 400 to 600 million cubic feet (at a pressure of 2100 psi). Two wells would probably have to be drilled as shown in the schematic Figure 2.1. Gas is contained in the nuclear storage cavity because the medium in which the shot is made is relatively impermeable. Both depth and geology have a determining effect on the amount of storage created at any given kiloton yield of nuclear explosion.

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* Carlson's study dates back to April, 1958.

At present it is possible to predict only the cavity volume with fair accuracy, but after Project Gasbuggy, the joint experiment in gas stimulation of U.S.A.E.C., Bureau of Mines and The El Paso Natural Gas Co. scheduled to be conducted in the Fall of 1967, other parameters of the storage method will also be better known.

Most of the natural gas used in the United States is produced in areas remote from the large consumer markets. Because the high pressure pipelines which move the gas to the consumer markets cost hundreds of millions of dollars to construct, it is economically necessary to operate these pipelines as near to maximum capacity as possible, in order to minimize pipeline gas costs. For many years purchasers buying gas in large volume have been developing gas storage facilities near the point of use. The major form of gas storage in the United States today is underground, either in depleted gas or oil fields from which the hydrocarbons have been exhausted, or by injecting gas into a subsurface water-bearing rock formation (aquifer storage). Storage at high pressures underground is not only safer than other methods (such as the use of refrigerated containers to hold liquified natural gas), it is also substantially cheaper. Moreover, these underground reservoirs are of a size to permit storage of the large quantities of gas needed to satisfy a major portion of the winter season requirements. The majority of this kind of gas storage is in depleted gas reservoirs [241]. The use of nuclear explosions to create underground storage would offer gas companies

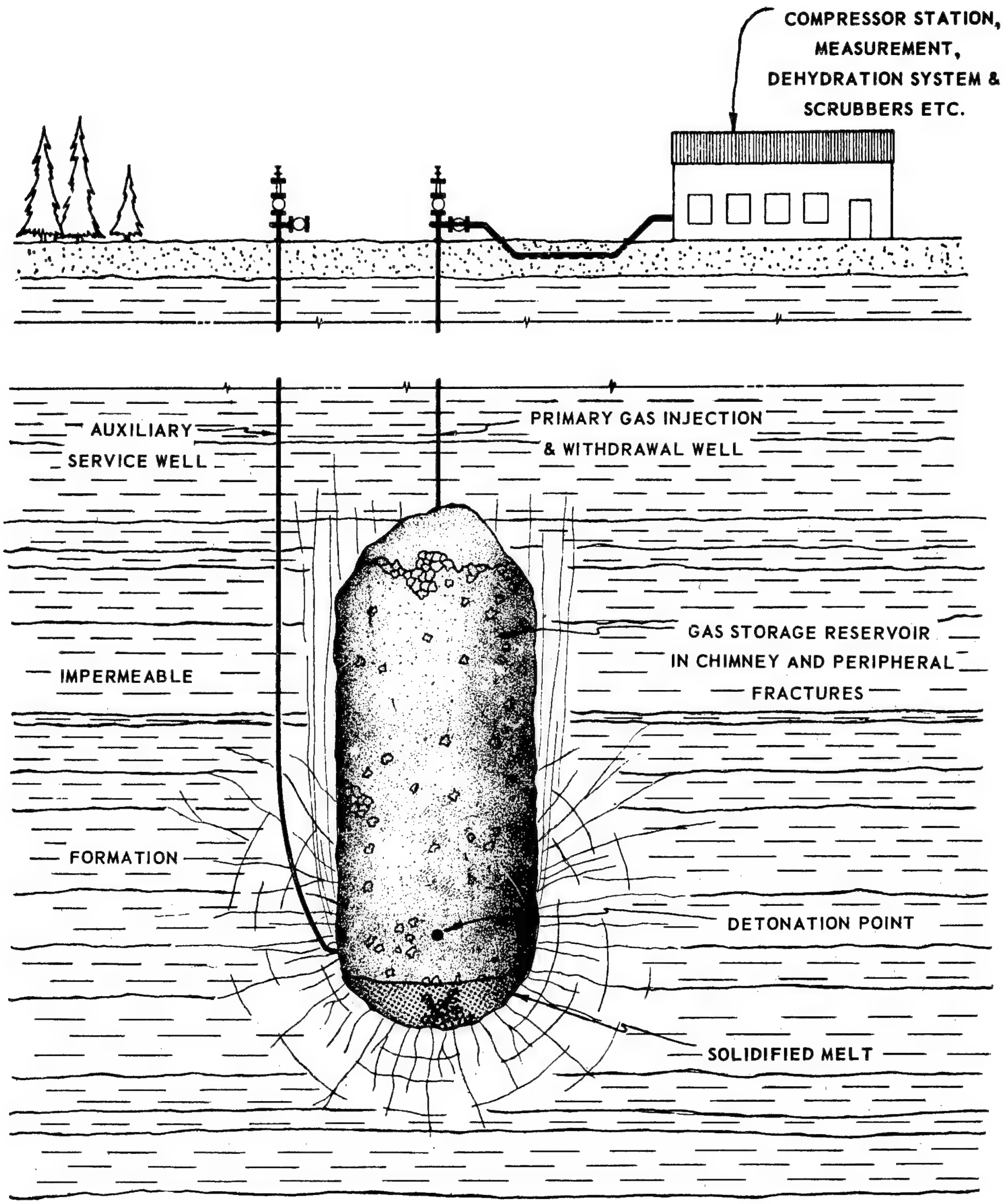
the advantage of being able to provide large amounts of additional storage in areas where naturally occurring underground storage is not available. Whether this advantage could be realized depends on the cost calculations.

Professor P. A. Witherspoon has pointed out [234] that a nuclear chimney has another distinct advantage: it is possible to produce gas from storage over a wide range of flow rates with essentially the same equipment. The highly fluctuating demand, both daily and seasonal, together with the relatively constant year-round production of gas in the field, creates a problem that gas companies can solve by providing adequate gas storage facilities [259]. It is a common occurrence for more than 50 per cent of a day's sendout to come from storage reservoirs. For a large gas company, the nuclear storage cavity might serve best in peak shaving operations where high rates of deliverability for short periods of time are required. On the other hand, there are many small companies where a low rate of production spread over the whole demand period could be very beneficial. The cost basis for a 24 kiloton field has been recently estimated [239] as \$.50 per thousand cubic feet of turnover, \$2.09 per MCF of peak day deliverability. The latter figure is highly competitive with conventional gas storage fields but the former is not.

2.2 PHENOMENOLOGY

The events which would occur following the detonation of an intermediate-range nuclear explosive device at considerable depth in an impermeable

Figure 2.1



GAS STORAGE IN A NUCLEAR RESERVOIR

SOURCE: Project Ketch Report on proposed experimental shot by Columbia Gas System Service Corp., USBM, USAEC and LRL, September, 1966.

geologic formation are frequently described in both the Special Reports and the General Report of MATHEMATICA on Plowshare. In one plausible experiment considered by the Columbia Gas System Service Corporation jointly with the USAEC, a 24-kiloton device detonated at a depth of 3300 feet in a shale formation is expected to create a cylindrical rubble chimney with a radius of ninety feet and a height of about three hundred feet. Cracks and fissures would extend upward above the cavity chimney for a distance of approximately three hundred feet. This estimate is important because on it depends not only the containment of radiation effects but also the ability of the cavity chimney to be a non-leaky container for natural gas.

For the normal case of a completely contained explosion which produces a "nuclear chimney" of the type described in the Introduction of this chapter, there is a rather well developed physical theory by which the void volume may be predicted as a function of depth of the shot point and yield (in kilotons) of the shot. Boardman and Toman [260] discussed the results of experiments in which five chimneys were pressurized to determine void volumes. These volumes, shown below in Table 2.1, conform to the formula for chimney storage volume:

$$V_c = \phi \cdot \frac{W(10^7)}{(\rho\ h)^{3/4}} \qquad (2.1)$$

in which W = yield in kilotons

ρ = average overburden density in gm./cc.

h = depth of burst in feet

ϕ = constant for rock medium

Table 2.1--Measured Chimney Void Volumes for Five Events

Medium	Event	Yield (KT)	Depth of burst (ft)	Average overburden density (g/cc)	Chimney void volume, (ft^3)
Salt	Gnome[8]	3.4 ± 0.5	1184	2.3	$1.0 \times 10^6 \pm 10\%$
	Salmon[9]	5.3 ± 0.5	2716	2.3	$0.69 \times 10^6 \pm 5\%$
Granite	Hardhat[5]	5.4 ± 1.0	939	2.7	$1.09 \times 10^6 \pm 3\%$
	Shoal[6]	13.4 ± 2.0	1205	2.7	$2.87 \times 10^6 \pm 8\%$
Dolomite	Handcar[7]	12.0 ± 1.0	1320	2.3	$1.41 \times 10^6 \pm 10\%$

SOURCE: Boardman, Charles R. and Toman, John, "Use of Nuclear Explosive Devices for Development of Underground Gas Storage Caverns," LRL, Livermore, California, UCRL-14746, April 20, 1966.

The value of ϕ has been estimated for various media: it would appear to range from 4.8 (dolomite) to about 16.0 or 17.0 (volcanic tuff). The authors conclude that the latter is the most desirable medium from the point of view of volume/KT yield, but point out that, unfortunately, the sites for potential volcanic tuff are virtually non-existent in the eastern half of the United States.

Translating the void volumes of Table 2.1 and the formula in Equation (2.1) into gas volumes at a standard pressure of 0.434 psi per foot of depth, and allowing for the effects of compressibility,

Witherspoon arrives at the following figures in millions of standard cubic feet.

Table 2.2--Gas Storage Volumes

in MMSCF

Depth in feet	Yield in KT	10	20	30	50	100
1000		82	164	246	409	818
2000		105	211	316	527	1,054
3000		120	239	359	598	1,196
4000		130	260	390	651	1,301
5000		139	277	416	693	1,386

SOURCE: Witherspoon, Paul A., "Economics of Nuclear Explosives in developing Underground Gas Storage," A.G.A. Transmission Conference, Dallas, Texas, May, 1966.

The simple linear increase across each line of the table is evident. Reading down any column, one finds with increasing depth, storage volume also increases for a fixed yield nuclear explosive device: this goes against Equation (2.1). The reason for this is the increasing pressure with depth more than compensating for the declining void volume. But the increase in storage volume as one goes down is not significant as an economic factor. Drilling costs are, at best, linear with depth and, unless a large-yield nuclear explosive device is to be used, they form a substantial part of the construction capital costs: accordingly economics suggest using the least depth compatible with safety and a leakproof storage cavity.

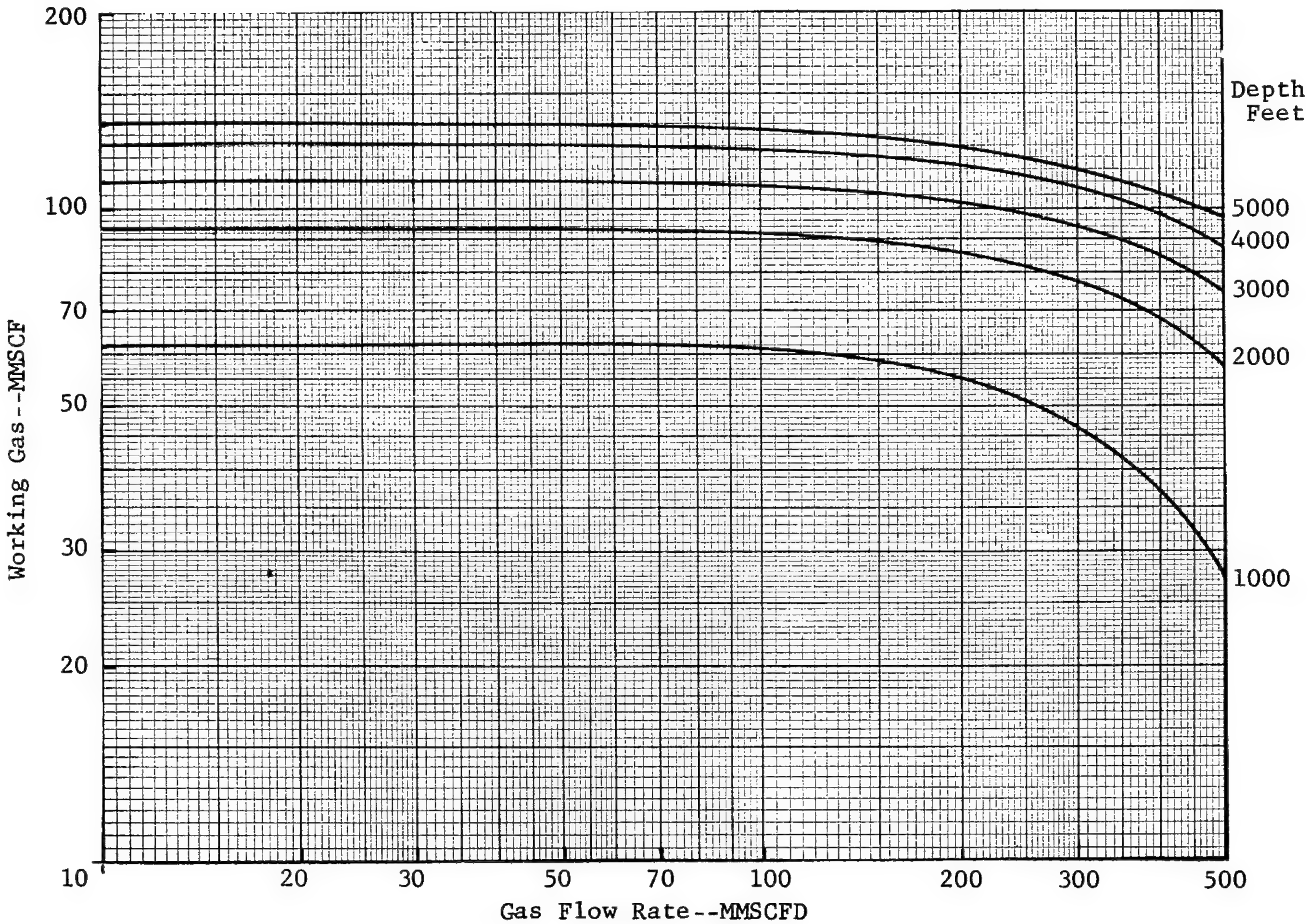
The permeable fractures around, and particularly <u>above</u> the shot point, have two effects. They may be expected to add up to 10 per cent

to the chimney volume [260]; and they constitute a prediction problem for an attempt to estimate the thickness of rock required to contain natural gas in a chimney and its fractured zone. While chimney height varies between one and four radii in competent rock, and up to about six radii in less competent rock [260], the maximum extent of fractures may be about eight cavity radii above shot point. Considerable uncertainty still pertains to this figure, however.

Witherspoon [234] discusses rates of production in relation to the size and depth of the nuclear storage cavern. The following two figures from that source show how the working gas varies with gas flow rate and depth; the third figure shows the production period as a function of depth for various flow rates and surface pressures. All three assume a 10 KT yield nuclear explosive device and a casing size of 13-5/8 inches.

If the yield is increased to 50 KT, the working gas volumes are multiplied by five because of the linear relation with yield. The choice of depth and yield can be made by a gas company in accordance with its operating requirements from the calculations of Witherspoon. Other considerations will probably determine the casing size of the emplacement hole. An interesting question is whether the emplacement hole can be used subsequently as a well. If it cannot, two wells would be drilled in addition to the emplacement hole. (In an experiment testing the proposed method of gas storage, many more wells would be drilled for observation and to provide some means of checking on the extent of the fracture pattern and detecting undesired gas migration.)

Figure 2.2

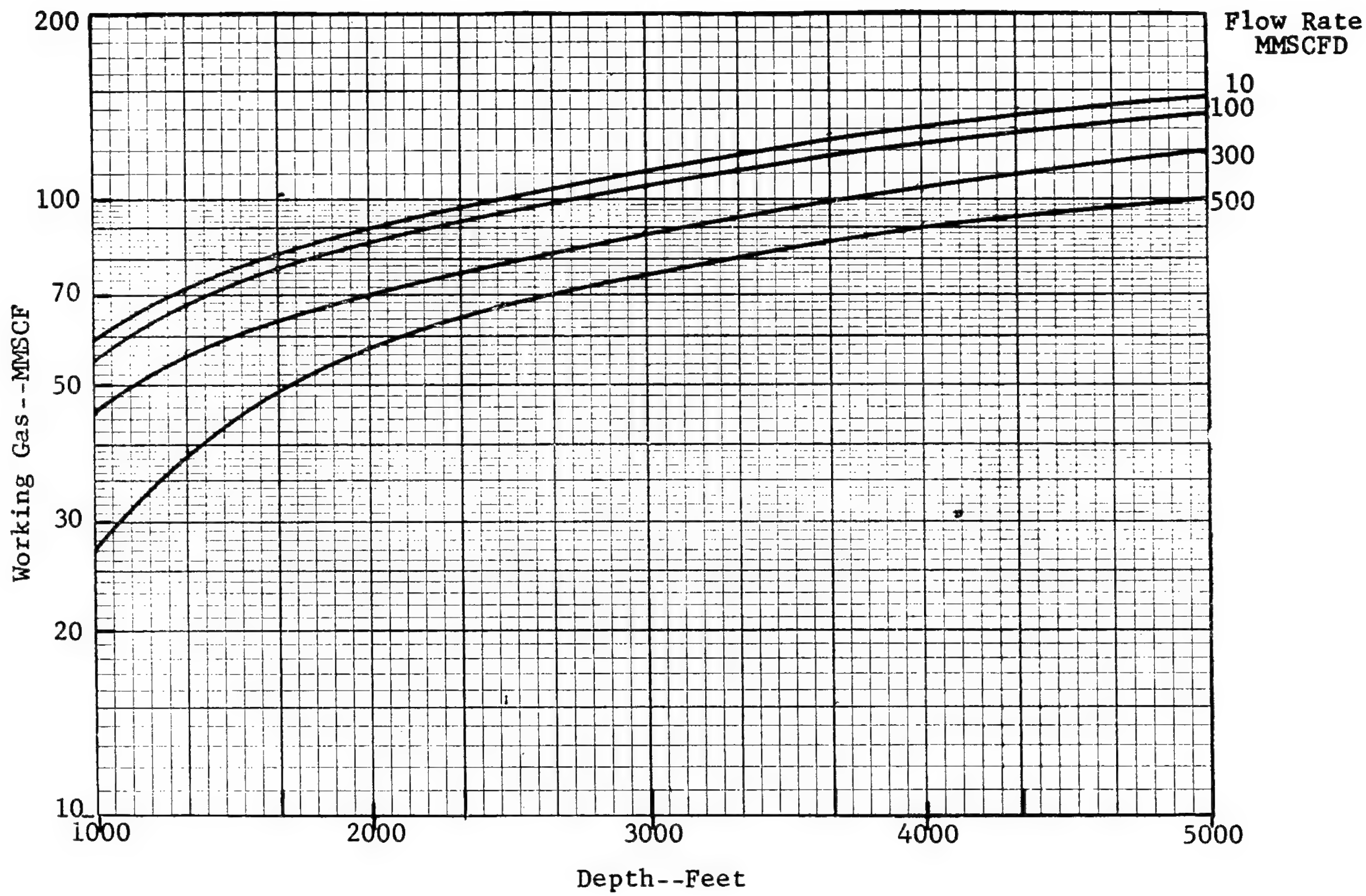


Assumed Conditions

Yield--10 KT
Casing Size--13 5/8"
Surface Pressure--100 psig

SOURCE: Witherspoon, Paul A., "Economics of Nuclear Explosives in Developing Underground Gas Storage," A.G.A. Transmission Conference, Dallas, Texas, May 9-11, 1966.

Figure 2.3

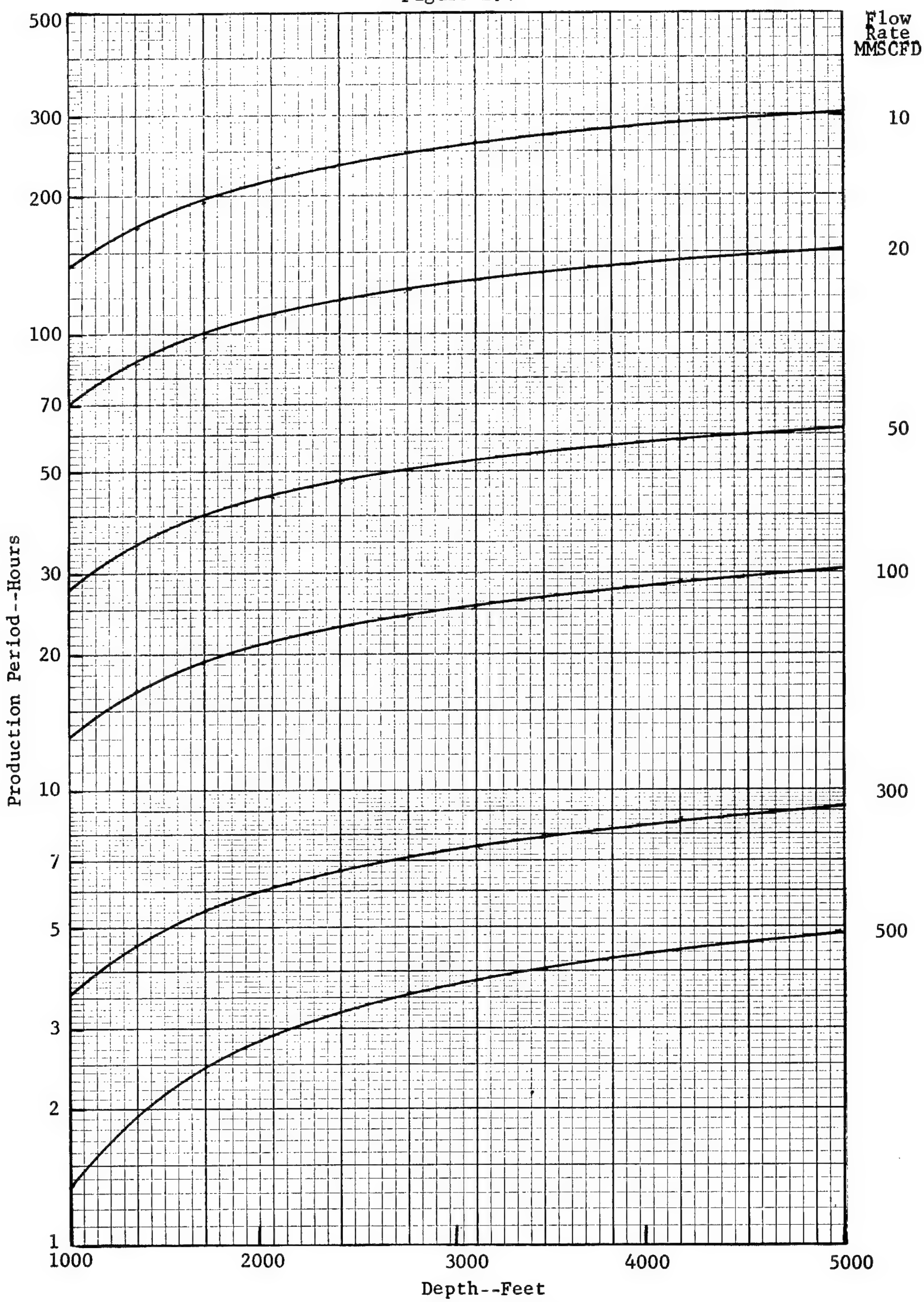


Assumed Conditions

Yield--10 KT
Casing Size--13 5/8"
Surface Pressure--100 psig

SOURCE: Witherspoon, Ibid.

Figure 2.4



Assumed Conditions

Yield--10 KT
Casing Size--13 5/8"
Surface Pressure--100 psig

SOURCE: Witherspoon, Ibid.

2.3 THE MACRO-ECONOMIC POTENTIAL OF NUCLEAR GAS STORAGE

The demand for natural gas as a fuel is intimately related with the availability and cost of storage near to the market area. In the Southwestern states, where most natural gas is produced, the relative cost of gas is low and the consumption rate per capita is at its highest. From Table 2.3, one sees that the six states of the Southwest have 12.5% of the national population, consume 24.2% of the natural gas sold by utilities and use only 9.6% of the total storage capacity. By contrast, the five Appalachian states have 16.5% of the population of the United States, consume 16.3% of the natural gas sold by utilities and use 34.4% of the storage capacity. The distance from gas-producing areas is not in itself a limiting factor for gas markets where low-cost storage is available, the gas may be transported economically through pipelines. Pipelines are very costly and represent a major investment by the gas companies. To make this investment profitable the "throughput" in the pipeline must be maintained at a fairly constant level and near to capacity. As the demand for gas is a highly seasonal one, winter demand showing a broad peak while production is relatively constant over the year, the condition of efficient pipeline usage is only met if much of the summer production goes into storage near the market, to be withdrawn when the winter peak arrives.

Gas may be stored in a variety of ways; the large gas tanks that are common in industrial areas around cities are a simple but expensive form. The Transcontinental Gas Pipe Line Corporation has a new multimillion dollar facility for converting natural gas into liquified form (LNG) near New York, and other LNG plants are now operating

Table 2.3--Regional Distribution of Gas Storage, Utility Sales, and Population

Producing Regions	Percentage of National Total		
	Population	Utility Sales of Gas	Gas Storage
Southwest States (6)	12.5	24.2	9.6
Pacific States (5)	11.8	14.7	6.2
Mountain States (8)	3.9	6.0	6.7
Consuming Regions with Storage			
Appalachian States (5)	16.5	16.3	34.4
North Central States (5)	16.6	17.3	31.4
Plains States (6)	6.7	8.6	7.8
Consuming Regions with Little or No Storage			
New England States (6)	5.8	1.7	0.0
South Atlantic States (6)	13.2	6.0	1.6
Middle Atlantic States (3)	13.0	5.2	2.3

Southwest States	- Alabama, Mississippi, Texas, Louisiana, Oklahoma, Arkansas
Pacific States	- California, Hawaii, Oregon, Washington, Alaska
Mountain States	- New Mexico, Colorado, Utah, Montana, Nevada, Wyoming, Idaho, Arizona
Appalachian States	- Ohio, West Virginia, Pennsylvania, Kentucky, Tennessee
North Central States	- Michigan, Indiana, Illinois, Wisconsin, Minnesota
Plain States	- Kansas, Missouri, Iowa, Nebraska, North Dakota, South Dakota
New England States	- Massachusetts, New Hampshire, Vermont, Maine, Connecticut, Rhode Island
South Atlantic States	- Maryland, Virginia, Georgia, North Carolina, South Carolina, District of Columbia, Florida
Middle Atlantic States	- New York, New Jersey, Delaware

SOURCE: Project Ketch, Report on proposed experimental shot by Columbia Gas System Service Corp., USBM, USAEC and Lawrence Radiation Laboratory, September 1966.

or under construction around the country. The construction costs and limited capacity make it economic to use these only for exceptional peaks in demand, e.g. when an exceptional cold spell in the weather occurs. In conjunction with the LNG plant, there are refrigerated storage containers, some of which are also underground. The major form of gas storage is underground, and this is the main alternative to tank storage. According to a survey conducted in the winter of 1965-66 by the American Gas Association [241], there were 4-5 trillions of cubic feet of storage capacity in the storage facilities of the major gas companies. The underground storage may be in depleted gas or oil fields from which the fuels have been exhausted, or in artificially created aquifer reservoirs formed by injecting gas into a subsurface water-bearing rock formation. In a few cases abandoned salt mines are used for gas storage [240].

Storage at high pressure underground is substantially cheaper (as well as safer) than the other methods metioned. Atkinson and Ward [259], in 1966, estimate that a nuclear underground storage cavern comparable to Transcontinental Gas Pipeline's $12 million LNG facility* would require investment of about $3 million, including surface facilities. Clearly less than this is needed where the underground void space can be created by non-nuclear means, as in the case of aquifer storage, since the cost of the nuclear explosive device and associated services is at least half of the investment. While daily and weekly fluctuations in demand can be supplied out of expensive tanks and LNG

*The early estimates for LNG storage were less than $2.00 per cu. ft. of liquid storage compared to $7.50 eventual.

(or liquid propane) storage, the underground storage reservoirs, with their large capacities, are needed to permit storage of enough gas to satisfy a major portion of the whole winter season requirements.

Inevitably, the broad potential of the nuclear storage method is dependent on the continuing growth of the gas market. As mentioned above the regional growth of demand for natural gas is related to the availability of low-cost storage near the regional markets. The Columbia Gas System has projected the underground storage requirements by assuming that areas with little or no storage currently would be developed on the same basis per capita as the Appalachian region: this would add 4 to 5 trillion cubic feet of capacity immediately, i.e. at current demand levels for well-supplied areas [239]. Taking the AGA prediction of slightly over 50% increase in total sales by 1975 they calculate a total storage need of 14 trillion cubic feet. In a sense this is rather a generous estimate of storage capacity requirements, since it fails to take account of a probable decline in reserves with an accompanying decline in gas production [20; but see 125 for a different picture if nuclear stimulation of gas reservoirs becomes a factor]. Furthermore, it assumes that the demand for natural gas from the major underground gas reservoirs grows unimpeded by competition from new forms of fuel or new processes for the conversion of fuels such as coal into gas. The gasification of coal has recently been demonstrated by the Consolidation Coal Company for the Office of Coal Research to be at least a possible competitor to the production of natural gas direct [261].

In view of the slow pace of development of commercial engineering by the use of underground nuclear explosions, it is probably quite unrealistic to base decisions about the future demand for underground natural gas storage caverns created by nuclear explosive devices on forecasts of total storage demand projected only eight years ahead.

2.4 MICRO-ECONOMICS OF NUCLEAR STORAGE

2.4.1 Introduction

Underground storage offers many gas companies very substantial savings over any other method of natural gas storage. Although the value of a storage field to the gas company depends crucially on the load factor at which its pipes operate,* the capital cost is always determined by the method of storage. Table 2.4 shows comparative figures in dollars per MCF of storage capacity. This provides only a first cut at the problem since deliverability rates, demand fluctuations, distances from producing wells and market area and many other variables enter into the final comparison in terms of cost of delivering an MCF to the customer.

Underground storage investment includes the cost of wells, cushion gas and gathering, dehydration and compression facilities. Cushion gas represents a sizable fraction of this investment in conventional underground storage fields (for instance 522 BCF of the 918 BCF of gas in storage in the United States was cushion gas in 1958). For nuclear cavity storage, it is currently believed that the ratio of delivery capacity to cushion gas will be much more favorable. For 181 United States storage fields, the average

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* It is usual for gas distribution companies to operate at load factors of about 50 per cent, whereas transmission pipelines must be operated closer to 100 per cent for the transmission company to make a profit.

Table 2.4--Capital Costs per MCF Capacity for Various Types of Storage

Type of Storage	Dollars/MCF
Sphere	227
Steel pipe (2,240 psi)	207
Steel pipe (980 psi)	110
Liquefaction: surface steel tank	4.85
mined cavern	5.50 to 6.45
dissolved salt cavern	4.20 to 4.30
Aquifer Storage	0.41
Depleted field storage	0.27
Nuclear cavity storage (24 KT)	3.34
Nuclear cavity storage (50 KT)	1.61
Nuclear cavity storage (100 KT)	1.04

SOURCES: *Project Ketch* Report on proposed experimental shot by Columbia Gas System Service Corp., USBM, USAEC and LRL, September, 1966.

Coats, Keith H., "Some Technical and Economic Aspects of Underground Gas Storage," *Journal of Petroleum Technology*, pp. 1561-1566, September, 1966.

depreciated investment costs in cents per MCF handled (injected or withdrawn), per MCF inventory (at year end) and per MCF delivery capacity are shown in Table 2.5. The final figure of $46.50 per MCF/D delivery capacity is an average cost for the 181 storage fields. For the 15 aquifer storage reservoirs alone, the cost per MCF/D is $66.

Turning now to the calculations of the Columbia Gas System Service Corporation, the U.S. Atomic Energy Commission and the U.S. Bureau of Mines in a feasibility study on creating natural gas storage with nuclear

Table 2.5--Average and Depreciated Investment Costs for 33 United States Pipeline Companies

Number of fields	
dry gas	146
water drive	20
aquifer	15
Total	181
Average BCF injected and withdrawn	714.97
Depreciated Storage Plant Investment (DSPI)	$618,679,353
15 % of above figure	92,801,902
Storage, operating and maintenance expense	28,533,939
Total Cost of Storing Gas	$121,335,841
Average Cost per MCF of Storage (cents)	
All fields	16.97 ¢
Dry gas fields	15.69 ¢
Water drive fields	16.52 ¢
Aquifers	24.17 ¢
Depreciated Investment Cost	
per MCF withdrawn	$ 0.92
per MCF inventory	$ 0.27
per MCF/D delivery capacity	$46.50

SOURCE: Coats, Keith H., "Some Technical and Economic Aspects of Underground Gas Storage," Journal of Petroleum Technology, pp. 1561-1566, September 1966.

explosions--Project Ketch, we find that the potential costs (Table 2.6) of nuclear fields very favorably compare with 181 United States conventional storage fields now in existence in terms of deliverability but unfavorably in terms of annual turnover at the conventional underground storage fields (see Table 2.7 below). At the same time, a very large peak day

Table 2.6--Potential Cost of Nuclear Gas Storage Reservoirs for Different Yields on a Non-Test Basis

	24 KT Field	50 KT Field	100 KT Field
	$	$	$
Reservoir Development	1,200,000	1,300,000	1,400,000
Gas Storage Facilities	351,000	456,000	685,000
Total Investment Cost	1,551,000	1,756,000	2,085,000
Annual Average Fixed Charges (11.29% - 11,00%)	175,000	198,000	235,000
Operating and Maintenance Costs	13,000	17,000	23,000
Total Annual Cost	188,000	215,000	258,000
Annual Average Cost/MCF Deliverability	2.09	1.43	1.03
Annual Average Cost/MCF	0.50	0.24	0.16

SOURCE: Project Ketch Report on proposed experimental shot by Columbia Gas System Service Corp, USBM, USAEC, and LRL, September 1966.

Table 2.7--Comparative Costs and Performances for Recently Developed Conventional Underground Storage Fields in the Columbia Gas System against Nuclear Storage Fields

	Year Developed	Total Investment Cost of Facilities $000	Average Annual Cost to Own & Operate $000	Annual Turnover MCF	Peak Day Deliver-ability MCF	Maximum Deliver-ability MCF	Annual Unit Cost to Own & Operate: of Turnover S/MCF	Annual Unit Cost to Own & Operate: Of Peak Day Deliver-ability S/MCF	Annual Unit Cost to Own & Operate: Of Maximum Deliver-ability S/MCF
Columbia Gas System Storage Fields									
Field A	1957	4,893	635	4,200,000	73,000	238,000	0.15	8.70	2.67
Field B	1958	5,520	646	2,500,000	80,000	114,000	0.26	8.07	5.67
Field C	1964	12,295	1,583	7,400,000	110,000	475,000	0.21	14.39	3.33
Field D	1960	23,032	2,627	13,985,000	255,000	340,000*	0.19	10.30	7.73
Field E	1964	18,913	2,263	12,195,000	240,000	580,000*	0.19	9.43	3.90
Field F	1967	18,519	2,112	8,400,000	110,000	280,000	0.25	19.20	7.54
Field G	1967	2,195	300	800,000	22,000	90,000	0.38	13.64	3.33
Nuclear Fields Foreseeable Cost Basis									
24-KT Field		1,551	188	375,000	90,000	90,000	0.50	2.09	2.09
50-KT Field		1,756	215	875,000	150,000	150,000	0.24	1.43	1.43
100-KT Field		2,085	258	1,600,000	250,000	250,000	0.16	1.03	1.03

* Lower Maximum deliverability because of pipeline facility limitations rather than reservoir limitations

SOURCE: Project Ketch, Ibid.

deliverability of 250,000 MCF/D will be achieved at a cost which is only 2 1/2 per cent of the average cost per MCF/D in 181 United States conventional underground gas storage fields.

2.4.2 Conditions for Success

The ability of a gas storage reservoir formed by nuclear explosions to be economically useful for its intended purpose is dependent on a number of rather obvious factors:

1. The chimney must contain the storage gas at working pressures without leaking. Reduction of storage pressure entails a serious additional cost.

2. The total storage capacity and the deliverability of the finished nuclear reservoir* must be large enough in relation to the investment of capital required to create it.

3. The radioactive contamination of gas that is ultimately (after a sufficient period of time) delivered from the reservoir must be low enough so that the cost of "cleaning" the gas does not raise its price above competitive deliveries. Some industries may be able to employ contaminated gas safely and in this case the radioactivity need not present a problem. Whenever gas is to be delivered into the customer's home for cooking or space heating, the necessity for it to be almost 100 per cent free from radioactive elements is obvious. Much work has been done on

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* including the fractures, whose void volume is much less predictable than the chimney void space.

removing the tritium [58, 71, 263] (see MATHEMATICA's General Report to U.S.A.E.C., p. 46); however there remains a large area of uncertainty concerning the level of tritium expectable in gas from a nuclear chimney several months after the detonation and another smaller area of uncertainty regarding the capital and operating costs of equipment capable of removing a very high percentage of the remaining tritium.

In view of these uncertainties it is only possible to anticipate for the time being that, after a period of experimentation, in which some actual experience with a nuclear gas reservoir such as the one recommended by Project Ketch would be gained, the costs of developing and operating nuclear reservoirs would be within a wide margin of feasibility which includes the rather optimistic figures shown in Table 2.8 below. Note that these figures do not include the cost of research which <u>must</u> precede development of commercial nuclear gas reservoirs.

In the Project Ketch report, Robert Forrest of CGS has computed that the break-even points for investment in a 24 KT nuclear reservoir are:

(i) $ 6,060,000 for a transmission company (own and operate)

(ii) $ 21,850,000 for a representative distribution company

The very wide differences between both these figures and the estimated total investment cost of $ 1,551,000 in Table 2.8 suggests that the nuclear reservoir offers a wide range of possibilities, some if not all of which will almost surely be economically attractive. Professor P. A. Witherspoon, in his final report to LRL on the "Economics of Underground

Table 2.8--Estimated Costs of Developing Nuclear Gas Storage Reservoirs

Reservoir Development	24-KT $	50-KT $	100-KT $
AEC Explosive Charges	390,000	425,000	460,000
Safety Studies and Precautions	400,000	400,000	400,000
Site Preparation	50,000	50,000	50,000
Emplacement Hole	125,000	150,000	175,000
Property Acquisition and Claim Investigation	80,000	100,000	120,000
Storage Re-entry	75,000	75,000	75,000
Cleanup of Chimney	40,000	50,000	60,000
Other Facilities	40,000	50,000	60,000
	1,200,000	1,300,000	1,400,000
Gas Storage Facilities			
Cushion Gas	36,000	86,000	160,000
Transmission Line	150,000	150,000	150,000
Compressor Station	165,000	220,000	375,000
	351,000	456,000	685,000
TOTAL INVESTMENT COST	1,551,000	1,756,000	2,085,000
Average Annual Fixed Charges (11.29% - 11.00%)	175,000	198,000	235,000
Operating & Maintenance Costs	13,000	17,000	23,000
	188,000	215,000	258,000
Average Annual Cost/MCF Deliverability	2.09	1.43	1.03
Average Annual Cost/MCF Turnover	0.50	0.24	0.16

SOURCE: Project Ketch, Ibid.

Gas Storage in Cavities Created by Nuclear Explosives," October 13, 1966 [264] agrees with this finding. He says that "there is much greater flexibility with this method than is normally the case in conventional underground storage." He also points out one advantage of a nuclear reservoir that "one can produce gas from storage over a very wide range of flow rates with essentially the same equipment." But, at the present time, enthusiasm must be tempered by a reminder that the geological conditions for a safe* and successful nuclear explosive creation of an underground gas reservoir impose a partially unknown, and possible severe limitation on the application of the method. This consideration is similar to the problem found in other parts of the Plowshare field and is well documented, e.g. [179, 263, 1, 75, 76, 265] . In some respects it is more limiting in the case of underground gas storage due to the need for a site near to market.

2.4.3 Conclusions

While the nuclear method of creating new underground gas reservoirs appears to have great promise in a number of specific areas, there is a clear indication that an experimental program should be undertaken before a major commitment of public or private funds is considered. The investment costs per MCF of storage for a 20 to 50 KT nuclear reservoir if detonation is at 2-4,000 feet below ground level are in the range of $1 to $4 (combining Witherspoon and Project Ketch estimates [234, 239]).

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* Reference is made here to the problem of determining the zones of acceptable levels of seismic damage to surface structures and underground pipelines in the vicinity of the nuclear explosive shot.

These compare favorably with some methods of creating gas storage such as LNG ($4 to $6.45), steel pipe ($110 to $207); and unfavorably with other underground methods (average 17 cents). In terms of deliverability the comparison is most favorable to the nuclear method ($1.43 to $2.09 as against an average of $46.50 for conventional storage fields).

Further research on the geologic settings which would be favorable to the nuclear method and its determination of locations for feasible application is indicated. More precise estimates of the levels of harmful radioactive materials in the nuclear reservoirs at various times subsequent to detonation would be required also to provide a complete picture of the cost of delivery of gas from storage.

Chapter 3

WASTE DISPOSAL

3.1 TYPES OF WASTE DISPOSAL PROBLEMS

The disposal of sewage and industrial effluents has received a vastly increased amount of attention in recent years as the streams, rivers and lakes of the United States have suffered increasingly from pollution. In some areas, population increases with no compensating change in the sewage disposal facilities result in a worsening quality of the water resource. In other areas, sewage and chemical wastes from booming industry combine to destroy the wildlife and/or the pleasing surface aspects of lakes and rivers. The problem is spreading at a rate which threatens to outstrip the best efforts of the anti-pollution fighters.

In 1959 municipalities spent about $100, 000, 000 [215] on water treatment. By today this figure may have multiplied fivefold. But still not enough is being done. Advanced chemical techniques for the treatment of water are mostly so costly that they will be applied only to drinking water (about one per cent of all water in public and private use.) Of all water returned to streams, rivers and lakes after industrial use, about 30 per cent is still untreated [215]. So long as the total amount of water being used remains a small percentage of the water resource, there

is no problem, providing that extremely harmful materials are excluded. But at the present accelerated rate of withdrawals of fresh water and returns of polluted water to the system, it is probably becoming necessary that all the major rivers and lakes should be "cleared" and put into proper mineral balance and biological balance. Such a program would be vast, requiring the annual expenditure of billions of dollars [231, p. 10].

A particular problem is the safe disposal of radioactive wastes. Although not large in volume, these are too dangerous to dump into the nearest waterway and hence must be diluted in advance to safe levels or buried deep in the ground. The groundwater in the vicinity must be constantly surveilled to prevent excessive radiation dosages entering the food chain. By 1959 a total of $200, 000, 000 capital had been outlaid on radioactive waste burial in the U. S. (mostly at Hanford, Washington and Oak Ridge, Tennessee) and an annual amount of $6, 000, 000 for maintenance was necessary [230, p. 203]. Some of the long-lasting radioactive material, after a process called "calcination" which converts them into a powder, have to be stored in long metal cannisters, which are buried in huge underground vaults. Others are diluted to appropriate levels and the fluid effluent is then injected hydraulically into a permeable layer thousands of feet below ground surface. Proposals for the use of abandoned salt mines have been considered in connection with the management of radioactive wastes, but long-distance transportation may prove to be a prohibitive cost and public menace. Plowshare could provide a large, safely

removed underground storage area for these "hot" wastes at reasonable costs, if the appropriate geological structure exists in the vicinity of the reactor or chemical processing plant (separator). The details of this proposal and related methods for the disposal of other waste fluids will be discussed in Section 3.2 below.

3.2 THE USE OF A CONTAINED NUCLEAR EXPLOSION FOR WASTE DISPOSAL

For the purposes of this project one of the most important features of underground explosions is the large increase of permeability of the rock medium surrounding the shot point (particularly above S.P.) [1]. Through the fractures which the explosion engenders for six or seven times the distance of one cavity radius, a waste fluid may flow into the permeable stratum selected for the purpose. This stratum must be bounded below by an impermeable rock and should be well isolated from aquifers which are directly connected to the water supplies of the region. The fission products from the explosion (such as Strontium 90) would be partly contained in a pool of radioactive glass which characteristically forms at the bottom of the chimney, and partly dispersed through the rubble and cracks in the surrounding formation. Its rate of transport through a permeable stratum is 40 times slower [1] than that of the water which carries it, so that only a minute quantity of the radioactivity released by the explosion would ever find its way into the environment. When radioactive wastes are to be injected into the nuclear chimney, the problem is of course more serious, but it is still quite conceivable to find a geological

formation in which the containment is adequate. For this purpose the use of relatively impermeable formations may be required, sacrificing storage volume but gaining permanent security from radioactive contamination of the environment [68].

In the case of non-radioactive waste disposal it is possible to consider the project a part of overall water management. The use of low-yield nuclear explosions for groundwater recharge has been proposed [221], and in this connection the basic purpose is similar, i.e., to improve the quality and quantity of the local water resource. It is not yet known whether the problems of managing the fission products can be solved in a water application. With the disposal of sewage and chemical wastes there is a trade-off between conventional processing costs and the risk of radioactive contamination of water supplies, but much more information is required before definite evaluation of the alternatives can be made.

Todd discusses several artificial recharge programs in [222]. Costs vary widely and the range for his selected examples is \$2 to \$50 per acre-foot. The single largest recharge project cost half a million dollars in El Rio, California, and involved a gross area of 125 acres. Three recharge pits operated by Los Angeles County Flood Control District cost \$45, \$3.50 and \$19.50 per acre-foot of water recharged. The total volumes of water involved (during twelve months) were respectively 1,000, 6,100 and 2,500 acre-feet. According to E. F. Renshaw quoted in [222]

the maximum value per acre-foot of water for waste disposal in the U. S. was $2.56 in 1950. Even allowing for today's higher prices, it does not appear that the use of nuclear technology is commercially competitive in this method. But to carry out a further analysis, we must also consider the alternative methods of treatment and disposal of wastes, and their costs.

3.3 THE PROBLEM OF DISPERSION VS. DISPOSAL

From the point of view of the riparian municipality, fluid wastes which are removed from the area by the river are disposed, but from a regional point of view--taking the whole river basin as a convenient region--they are only dispersed and diluted. Much effort has gone into the economic study of Water Management recently, and a number of proposals have been made to achieve an equitable distribution of the user costs associated with the avoidance of pollution in public bodies of water. See for instance [232].

The burning of solid and gaseous wastes is an inexpensive way of disposing of a major fraction of many waste materials--from the narrow point of view of the firm or municipality doing the burning. So long as the dispersion is effective, there is no problem; but sooner or later industrial and population concentrations will cause air pollution. At such time, the wastes are no longer disposed of, public health is threatened, and legislation comes into being to limit the quantity of harmful waste substance through burning into the atmosphere. Again, as with the fluid

wastes, disposal is really dispersion; and the limits of the environmental capacity to absorb and dilute the wastes are rapidly approached under a system of "free" dispersion.

In the case of wastes which are extremely dangerous, there has been for some time a rather tight control on their release to the environment. The various unwanted radioisotopes produced at Oak Ridge and Hanford [230] having half-lives of more than a few days, must be first stored; then they may be released if the radioactive decay is sufficiently advanced or, more likely, they are reduced in bulk and permanently stored by burial. In one method [233], the radioactive wastes are reduced to solids using a pot calcination process. The "pot," a steel cylinder, six to eight feet tall and eight to eighteen inches in diameter, becomes the permanent container for the calcined product. It is sealed and stored underground. The pot itself is designed to last for twenty or thirty years under stable environmental conditions. Although the method is expensive, it appears to be well within the feasible range as far as the system costs are concerned. Studies carried out at Oak Ridge showed that, for a reactor plant the various steps required for the management of radioactive wastes from power reactor fuel processing would cause a total incremental cost of 0.03 mill* per kwh--or about one per cent of the total reactor fuel cycle cost. These steps included interim storage of the wastes as liquid in tanks, pot calcination to produce relatively smaller volumes of thermally

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* 1 mill = one thousandth of a dollar.

stable solids, and finally shipment of the pots to the place of permanent disposal.

The principle in the above-mentioned treatment and disposal of radioactive wastes is quite different from dispersion. On the contrary, they are concentrated into compact containers, isolated from the biosphere and temporarily or permanently stored in isolation. The major reason for the application of the method in the case of radioactive wastes is the high cost of "treatment." Unlike most other industrial wastes, there is no reasonable process available for rendering the waste material harmless so that it might be subsequently dispersed. For a power reactor, shipment of the calcined wastes even as far as 1,000 miles does not impose intolerable burdens on the economy of the electricity production. Conceivably a problem might arise if the total quantity of these extremely dangerous cargoes required to be transported nationwide, within one year, exceeded some threshold, since the likelihood of an accident would then begin to have a significant effect on the waste disposal costs. But otherwise it remains a remarkable fact that any waste product--in itself of zero value--should be transported considerable distances within the economic framework of a single production unit.

The application of nuclear explosives for creating underground storage for harmful wastes is an alternative to the existing methods which at present does not appear to demand substantive investment of resources,

but which could prove to be a valuable addition to the Federal anti-pollution program particularly if used in conjunction with a regional water resource management scheme.

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